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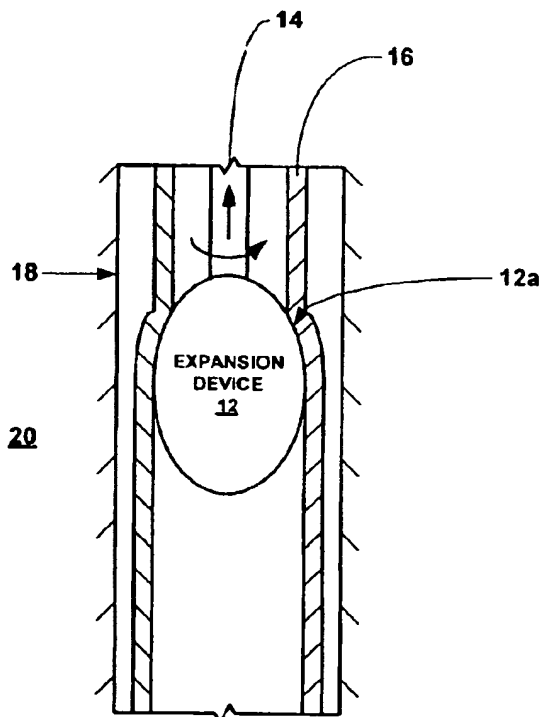
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(54) Title: LUBRICATION SYSTEM FOR RADIALY EXPANDING TUBULAR MEMBERS



(57) Abstract: A lubrication system for lubricating an interface between one or more expansion surfaces of an expansion device and one or more interior surfaces of a tubular member during a radial expansion of the tubular member using the expansion device.

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**LUBRICATION SYSTEM FOR RADIALLY EXPANDING TUBULAR MEMBERS****Cross Reference To Related Applications**

**[001]** The present application claims the benefit of the filing date of U.S. provisional patent application serial no. 60/442,938, attorney docket no. 25791.225, filed on January 27, 2003, the disclosure of which is incorporated herein by reference.

**[002]** The present application is related to the following: (1) U.S. patent application serial no. 09/454,139, attorney docket no. 25791.03.02, filed on 12/3/1999, (2) U.S. patent application serial no. 09/510,913, attorney docket no. 25791.7.02, filed on 2/23/2000, (3) U.S. patent application serial no. 09/502,350, attorney docket no. 25791.8.02, filed on 2/10/2000, (4) U.S. patent application serial no. 09/440,338, attorney docket no. 25791.9.02, filed on 11/15/1999, (5) U.S. patent application serial no. 09/523,460, attorney docket no. 25791.11.02, filed on 3/10/2000, (6) U.S. patent application serial no. 09/512,895, attorney docket no. 25791.12.02, filed on 2/24/2000, (7) U.S. patent application serial no. 09/511,941, attorney docket no. 25791.16.02, filed on 2/24/2000, (8) U.S. patent application serial no. 09/588,946, attorney docket no. 25791.17.02, filed on 6/7/2000, (9) U.S. patent application serial no. 09/559,122, attorney docket no. 25791.23.02, filed on 4/26/2000, (10) PCT patent application serial no. PCT/US00/18635, attorney docket no. 25791.25.02, filed on 7/9/2000, (11) U.S. provisional patent application serial no. 60/162,671, attorney docket no. 25791.27, filed on 11/1/1999, (12) U.S. provisional patent application serial no. 60/154,047, attorney docket no. 25791.29, filed on 9/16/1999, (13) U.S. provisional patent application serial no. 60/159,082, attorney docket no. 25791.34, filed on 10/12/1999, (14) U.S. provisional patent application serial no. 60/159,039, attorney docket no. 25791.36, filed on 10/12/1999, (15) U.S. provisional patent application serial no. 60/159,033, attorney docket no. 25791.37, filed on 10/12/1999, (16) U.S. provisional patent application serial no. 60/212,359, attorney docket no. 25791.38, filed on 6/19/2000, (17) U.S. provisional patent application serial no. 60/165,228, attorney docket no. 25791.39, filed on 11/12/1999, (18) U.S. provisional patent application serial no. 60/221,443, attorney docket no. 25791.45, filed on 7/28/2000, (19) U.S. provisional patent application serial no. 60/221,645, attorney docket no. 25791.46, filed on 7/28/2000, (20) U.S. provisional patent application serial no. 60/233,638, attorney docket no. 25791.47, filed on 9/18/2000, (21) U.S. provisional patent application serial no. 60/237,334, attorney docket no. 25791.48, filed on 10/2/2000, (22) U.S. provisional patent application serial no. 60/270,007,

attorney docket no. 25791.50, filed on 2/20/2001, (23) U.S. provisional patent application serial no. 60/262,434, attorney docket no. 25791.51, filed on 1/17/2001, (24) U.S. provisional patent application serial no. 60/259,486, attorney docket no. 25791.52, filed on 1/3/2001, (25) U.S. provisional patent application serial no. 60/303,740, attorney docket no. 25791.61, filed on 7/6/2001, (26) U.S. provisional patent application serial no. 60/313,453, attorney docket no. 25791.59, filed on 8/20/2001, (27) U.S. provisional patent application serial no. 60/317,985, attorney docket no. 25791.67, filed on 9/6/2001, (28) U.S. provisional patent application serial no. 60/3318,386, attorney docket no. 25791.67.02, filed on 9/10/2001, (29) U.S. utility patent application serial no. 09/969,922, attorney docket no. 25791.69, filed on 10/3/2001, (30) U.S. utility patent application serial no. 10/016,467, attorney docket no. 25791.70, filed on December 10, 2001, (31) U.S. provisional patent application serial no. 60/343,674, attorney docket no. 25791.68, filed on 12/27/2001; and (32) U.S. provisional patent application serial no. 60/346,309, attorney docket no. 25791.92, filed on 01/07/02, the disclosures of which are incorporated herein by reference.

### **Background of the Invention**

**[003]** This invention relates generally to oil and gas exploration, and in particular to forming and repairing wellbore casings to facilitate oil and gas exploration.

**[004]** During oil exploration, a wellbore typically traverses a number of zones within a subterranean formation. Wellbore casings are then formed in the wellbore by radially expanding and plastically deforming tubular members that are coupled to one another by threaded connections. Existing methods for radially expanding and plastically deforming tubular members coupled to one another by threaded connections are not always reliable or produce satisfactory results. In particular, the threaded connections can be damaged during the radial expansion process.

**[005]** During expansion, an expansion cone is moved axially through the tubular members. The cone has an outside diameter greater than the inside diameter of the tubular members. Thus, a tremendous amount of friction exists between the cone and the tubular members which results in heat, stress and wear.

**[006]** The expansion cone, or mandrel, is used to permanently mechanically deform the pipe. The cone is moved through the tubing by a differential hydraulic pressure across the cone itself, and/or by a direct mechanical pull or push force. The

differential pressure is pumped through an inner-string connected to the cone, and the mechanical force is applied by either raising or lowering the inner string.

**[007]** Progress of the cone through the tubing deforms the steel beyond its elastic limit into the plastic region, while keeping stresses below ultimate yield.

**[008]** Contact between cylindrical mandrel and pipe ID during expansion leads to significant forces due to friction. It would be beneficial to provide a mandrel which could reduce friction during the expansion process.

**[009]** The present invention is directed to overcoming one or more of the limitations of the existing processes for radially expanding and plastically deforming tubular members coupled to one another by threaded connections.

### **Summary Of The Invention**

**[0010]** According to one aspect of the present invention, an expansion cone for radially expanding multiple tubular members is provided that includes a body having an annular outer peripheral surface, and at least a portion of the surface being textured with friction reducing reliefs recessed into the surface.

**[0011]** According to another aspect of the present invention, a reduced friction radial expansion apparatus is provided that includes a plurality of tubular members having an axial passage formed therethrough including an inside diameter, an expansion cone having an annular outer peripheral surface including an outside diameter greater than the inside diameter of the axial passage, and at least a portion of the outer peripheral surface being textured with friction reducing reliefs recessed into the surface.

**[0012]** According to another aspect of the present invention, an apparatus for radially expanding and plastically deforming a tubular member is provided that includes a support member, an expansion device coupled to an end of the support member comprising one or more expansion surfaces for engaging the tubular member during the radial expansion and plastic deformation of the tubular member, and a lubrication system for lubricating an interface between one or more of the expansion surfaces of the expansion device and one or more interior surfaces of the tubular member.

**[0013]** According to another aspect of the present invention, a method for radially expanding and plastically deforming a tubular member is provided that includes radially expanding and plastically deforming the tubular member using an expansion device comprising one or more expansion surfaces, and lubricating an interface

between one or more of the expansion surfaces of the expansion device and one or more interior surfaces of the tubular member.

**[0014]** According to another aspect of the present invention, a system for lubricating an interface between an expansion device and a tubular member during a radial expansion of the tubular member by the expansion device is provided that includes means for supplying a quantity of a lubricant material, and means for injecting at least a portion of the lubricant material into the interface.

**[0015]** According to another aspect of the present invention, a method of operating a system for lubricating an interface between an expansion device and a tubular member during a radial expansion of the tubular member by the expansion device is provided that includes determining a rate of strain of the tubular member during an operation of the expansion device, and varying a concentration of a lubricant material within the interface during the operation of the expansion device as a function of the determined rate of strain.

**[0016]** According to another aspect of the present invention, a method of operating a system for lubricating an interface between an expansion device and a tubular member during a radial expansion of the tubular member by the expansion device is provided that includes determining one or more characteristics of the interface during an operation of the expansion device, and varying a concentration of a lubricant material within the interface during the operation of the expansion device as a function of one or more of the determined characteristics.

**[0017]** According to another aspect of the present invention, a system for lubricating an interface between an expansion device and a tubular member during a radial expansion of the tubular member by the expansion device is provided that includes means for determining a rate of strain of the tubular member during an operation of the expansion device, and means for varying a concentration of a lubricant material within the interface during the operation of the expansion device as a function of the determined rate of strain.

**[0018]** According to another aspect of the present invention, a system for lubricating an interface between an expansion device and a tubular member during a radial expansion of the tubular member by the expansion device is provided that includes means for determining one or more characteristics of the interface during an operation of the expansion device, and means for varying a concentration of a

lubricant material within the interface during the operation of the expansion device as a function of one or more of the determined characteristics.

**[0019]** According to another aspect of the present invention, a method of operating a system for lubricating an interface between an expansion device and a tubular member during a radial expansion of the tubular member by the expansion device is provided that includes determining one or more characteristics of the operation of the expansion device, and varying a concentration of a lubricant material within the interface during the operation of the expansion device as a function of one or more of the determined characteristics.

**[0020]** According to another aspect of the present invention, a system for lubricating an interface between an expansion device and a tubular member during a radial expansion of the tubular member by the expansion device is provided that includes means for determining one or more characteristics of the operation of the expansion device, and means for varying a concentration of a lubricant material within the interface during the operation of the expansion device as a function of one or more of the determined characteristics.

**[0021]** According to another aspect of the present invention, a tribological system for lubricating an interface between an expansion device and a tubular member during a radial expansion and plastic deformation of the tubular member is provided that includes an expansion surface coupled to the expansion device defining a surface texture, a first lubricating film coupled to the expansion surface, a second lubricating film coupled to an interior surface of the tubular member, and a lubricating material disposed within an annulus defined between the expansion surface of the expansion device and the interior surface of the tubular member.

**[0022]** According to another aspect of the present invention, a method of lubricating an interface between an expansion surface of an expansion device and a tubular member during a radial expansion and plastic deformation of the tubular member is provided that includes texturing the expansion surface, coupling a first lubricating film coupled to the expansion surface, coupling a second lubricating film to an interior surface of the tubular member, and disposing a lubricating material within an annulus defined between the expansion surface of the expansion device and the interior surface of the tubular member.

**[0023]** According to another aspect of the present invention, a system for radially expanding and plastically deforming a tubular member is provided in which the

amount of energy required to overcome frictional forces during the radial expansion and plastic deformation of the tubular member is less than or equal to 8% of the total amount of energy required to radially expand and plastically deform the tubular member.

**[0024]** According to another aspect of the present invention, a system for radially expanding and plastically deforming a tubular member is provided including an expansion device, wherein the coefficient of friction between the expansion device and the tubular member during the radial expansion and plastic deformation of the tubular member is less than or equal to 0.06.

#### **Brief Description of the Drawings**

**[0025]** Fig. 1a is a fragmentary cross-sectional view illustrating an exemplary embodiment of an apparatus for radially expanding and plastically deforming a tubular member.

**[0026]** Fig. 1b is a fragmentary cross-sectional illustration of an exemplary embodiment of the operation of the apparatus of Fig. 1a..

**[0027]** Fig. 2 is a fragmentary cross-sectional illustration of an exemplary embodiment of the apparatus of Figs. 1a and 1b including a lubricant supply.

**[0028]** Fig. 3 is a fragmentary cross-sectional illustration of an exemplary embodiment of the apparatus of Figs. 1a and 1b including a lubricant supply.

**[0029]** Fig. 4 is a fragmentary cross-sectional illustration of an exemplary embodiment of the apparatus of Figs. 1a and 1b including a lubricant coating.

**[0030]** Fig. 5 is a fragmentary cross-sectional illustration of an exemplary embodiment of the apparatus of Figs. 1a and 1b including a lubricant coating.

**[0031]** Fig. 6 is a fragmentary cross-sectional illustration of an exemplary embodiment of an exemplary portion of the external surface of the expansion device of the apparatus of Figs. 1a and 1b including one or more recesses defined in the external surface.

**[0032]** Fig. 7 is a fragmentary cross-sectional illustration of an exemplary embodiment of the apparatus of Fig. 6.

**[0033]** Fig. 8 is a fragmentary cross-sectional illustration of an exemplary embodiment of an exemplary portion of the external surface of the expansion device of the apparatus of Figs. 1a and 1b including one or more recesses defined in the external surface.



**[0034]** Fig. 9 is a fragmentary cross-sectional illustration of an exemplary embodiment of the apparatus of Fig. 8.

**[0035]** Fig. 10 is a fragmentary cross-sectional illustration of an exemplary embodiment of an exemplary portion of the external surface of the expansion device of the apparatus of Figs. 1a and 1b including one or more recesses defined in the external surface.

**[0036]** Fig. 11 is a fragmentary cross-sectional illustration of an exemplary embodiment of the apparatus of Fig. 10.

**[0037]** Fig. 12 is a fragmentary cross-sectional illustration of an exemplary embodiment of an exemplary portion of the external surface of the expansion device of the apparatus of Figs. 1a and 1b including one or more recesses defined in the external surface.

**[0038]** Fig. 13 is a fragmentary cross-sectional illustration of an exemplary embodiment of the apparatus of Fig. 12.

**[0039]** Fig. 14 is a fragmentary cross-sectional illustration of an exemplary embodiment of an exemplary portion of the external surface of the expansion device of the apparatus of Figs. 1a and 1b including one or more recesses defined in the external surface.

**[0040]** Fig. 15 is a fragmentary cross-sectional illustration of an exemplary embodiment of the apparatus of Fig. 14.

**[0041]** Fig. 16 is a fragmentary cross-sectional illustration of an exemplary embodiment of an exemplary portion of the external surface of the expansion device of the apparatus of Figs. 1a and 1b including one or more recesses defined in the external surface.

**[0042]** Fig. 17 is a fragmentary cross-sectional illustration of an exemplary embodiment of the apparatus of Fig. 16.

**[0043]** Fig. 18 is a fragmentary cross-sectional illustration of an exemplary embodiment of an exemplary portion of the external surface of the expansion device of the apparatus of Figs. 1a and 1b including one or more recesses defined in the external surface.

**[0044]** Fig. 19 is a fragmentary cross-sectional illustration of an exemplary embodiment of the apparatus of Fig. 18.

**[0045]** Fig. 20 is a fragmentary cross-sectional illustration of an exemplary embodiment of an exemplary portion of the external surface of the expansion device

of the apparatus of Figs. 1a and 1b including one or more recesses defined in the external surface.

**[0046]** Fig. 21 is a fragmentary cross-sectional illustration of an exemplary embodiment of the apparatus of Fig. 20.

**[0047]** Fig. 22 is a fragmentary cross-sectional illustration of an exemplary embodiment of leading and trailing edges of the interface between the expansion device of the apparatus of Figs. 1a and 1b and the tubular member during the radial expansion and plastic deformation of the tubular member.

**[0048]** Fig. 23 is an exemplary embodiment of a graphical illustration of the concentration distribution of lubrication elements in the external surface of the expansion device of the apparatus of Figs. 1a and 1b.

**[0049]** Fig. 24 is a fragmentary cross-sectional illustration of an exemplary embodiment of the interface between the expansion device of the apparatus of Figs. 1a and 1b and the tubular member during the radial expansion and plastic deformation of the tubular member.

**[0050]** Fig. 25 is an exemplary embodiment of a graphical illustration of the concentration distribution of lubrication elements in the external surface of the expansion device of the apparatus of Figs. 1a and 1b.

**[0051]** Fig. 26 is an exemplary embodiment of a graphical illustration of the concentration distribution of lubrication elements in the external surface of the expansion device of the apparatus of Figs. 1a and 1b.

**[0052]** Fig. 27 is an exemplary embodiment of a graphical illustration of the concentration distribution of lubrication elements in the external surface of the expansion device of the apparatus of Figs. 1a and 1b.

**[0053]** Fig. 28 is an exemplary embodiment of a graphical illustration of the concentration distribution of lubrication elements in the external surface of the expansion device of the apparatus of Figs. 1a and 1b.

**[0054]** Fig. 29 is an exemplary embodiment of a graphical illustration of the concentration distribution of lubrication elements in the external surface of the expansion device of the apparatus of Figs. 1a and 1b.

**[0055]** Fig. 30 is an exemplary embodiment of the apparatus of Figs. 1a and 1b.

**[0056]** Figs. 31a, 31b, 31c, and 31d are illustrations of an exemplary embodiment of the apparatus of Figs. 1a and 1b.

**[0057]** Figs. 32a, 32b, 32c, and 32d are illustrations of an exemplary embodiment of the apparatus of Figs. 1a and 1b.

**[0058]** Fig. 33 is a schematic illustration of a tribological system.

#### **Detailed Description of the Illustrative Embodiments**

**[0059]** Referring to Figs. 1a and 1b, an exemplary embodiment of an apparatus 10 for radially expanding a tubular member includes an expansion device 12 including one or more expansion surfaces 12a that is coupled to an end of a support member 14.

**[0060]** In an exemplary embodiment, the expansion device 12 is a conventional commercially available expansion device and/or is provided substantially as described in one or more of the following: : (1) U.S. patent application serial no. 09/454,139, attorney docket no. 25791.03.02, filed on 12/3/1999, (2) U.S. patent application serial no. 09/510,913, attorney docket no. 25791.7.02, filed on 2/23/2000, (3) U.S. patent application serial no. 09/502,350, attorney docket no. 25791.8.02, filed on 2/10/2000, (4) U.S. patent application serial no. 09/440,338, attorney docket no. 25791.9.02, filed on 11/15/1999, (5) U.S. patent application serial no. 09/523,460, attorney docket no. 25791.11.02, filed on 3/10/2000, (6) U.S. patent application serial no. 09/512,895, attorney docket no. 25791.12.02, filed on 2/24/2000, (7) U.S. patent application serial no. 09/511,941, attorney docket no. 25791.16.02, filed on 2/24/2000, (8) U.S. patent application serial no. 09/588,946, attorney docket no. 25791.17.02, filed on 6/7/2000, (9) U.S. patent application serial no. 09/559,122, attorney docket no. 25791.23.02, filed on 4/26/2000, (10) PCT patent application serial no. PCT/US00/18635, attorney docket no. 25791.25.02, filed on 7/9/2000, (11) U.S. provisional patent application serial no. 60/162,671, attorney docket no. 25791.27, filed on 11/1/1999, (12) U.S. provisional patent application serial no. 60/154,047, attorney docket no. 25791.29, filed on 9/16/1999, (13) U.S. provisional patent application serial no. 60/159,082, attorney docket no. 25791.34, filed on 10/12/1999, (14) U.S. provisional patent application serial no. 60/159,039, attorney docket no. 25791.36, filed on 10/12/1999, (15) U.S. provisional patent application serial no. 60/159,033, attorney docket no. 25791.37, filed on 10/12/1999, (16) U.S. provisional patent application serial no. 60/212,359, attorney docket no. 25791.38, filed on 6/19/2000, (17) U.S. provisional patent application serial no. 60/165,228, attorney docket no. 25791.39, filed on 11/12/1999, (18) U.S. provisional patent application serial no. 60/221,443, attorney docket no. 25791.45, filed on

7/28/2000, (19) U.S. provisional patent application serial no. 60/221,645, attorney docket no. 25791.46, filed on 7/28/2000, (20) U.S. provisional patent application serial no. 60/233,638, attorney docket no. 25791.47, filed on 9/18/2000, (21) U.S. provisional patent application serial no. 60/237,334, attorney docket no. 25791.48, filed on 10/2/2000, (22) U.S. provisional patent application serial no. 60/270,007, attorney docket no. 25791.50, filed on 2/20/2001, (23) U.S. provisional patent application serial no. 60/262,434, attorney docket no. 25791.51, filed on 1/17/2001, (24) U.S. provisional patent application serial no. 60/259,486, attorney docket no. 25791.52, filed on 1/3/2001, (25) U.S. provisional patent application serial no. 60/303,740, attorney docket no. 25791.61, filed on 7/6/2001, (26) U.S. provisional patent application serial no. 60/313,453, attorney docket no. 25791.59, filed on 8/20/2001, (27) U.S. provisional patent application serial no. 60/317,985, attorney docket no. 25791.67, filed on 9/6/2001, (28) U.S. provisional patent application serial no. 60/3318,386, attorney docket no. 25791.67.02, filed on 9/10/2001, (29) U.S. utility patent application serial no. 09/969,922, attorney docket no. 25791.69, filed on 10/3/2001, (30) U.S. utility patent application serial no. 10/016,467, attorney docket no. 25791.70, filed on December 10, 2001, (31) U.S. provisional patent application serial no. 60/343,674, attorney docket no. 25791.68, filed on 12/27/2001; and (32) U.S. provisional patent application serial no. 60/346,309, attorney docket no. 25791.92, filed on 01/07/02, the disclosures of which are incorporated herein by reference. In several alternative embodiments, the expansion device 12 is, or includes, a conventional commercially available rotary expansion device such, for example, those available from Weatherford International.

**[0061]** In an exemplary embodiment, the apparatus 10 is operated to radially expand and plastically deform a tubular member 16 by displacing and/or rotating the expansion device 12 relative to the tubular member 16 within a preexisting structure such as, for example, a wellbore 18 that traverses a subterranean formation 20. In an exemplary embodiment, during the operation of the apparatus 10, the expansion surface 12a of the expansion device 12 engages at least a portion of the interior surface 16a of the tubular member 16.

**[0062]** In an exemplary embodiment, the apparatus 10 is operated substantially as described in one or more of the following: (1) U.S. patent application serial no. 09/454,139, attorney docket no. 25791.03.02, filed on 12/3/1999, (2) U.S. patent application serial no. 09/510,913, attorney docket no. 25791.7.02, filed on 2/23/2000,

(3) U.S. patent application serial no. 09/502,350, attorney docket no. 25791.8.02, filed on 2/10/2000, (4) U.S. patent application serial no. 09/440,338, attorney docket no. 25791.9.02, filed on 11/15/1999, (5) U.S. patent application serial no. 09/523,460, attorney docket no. 25791.11.02, filed on 3/10/2000, (6) U.S. patent application serial no. 09/512,895, attorney docket no. 25791.12.02, filed on 2/24/2000, (7) U.S. patent application serial no. 09/511,941, attorney docket no. 25791.16.02, filed on 2/24/2000, (8) U.S. patent application serial no. 09/588,946, attorney docket no. 25791.17.02, filed on 6/7/2000, (9) U.S. patent application serial no. 09/559,122, attorney docket no. 25791.23.02, filed on 4/26/2000, (10) PCT patent application serial no. PCT/US00/18635, attorney docket no. 25791.25.02, filed on 7/9/2000, (11) U.S. provisional patent application serial no. 60/162,671, attorney docket no. 25791.27, filed on 11/1/1999, (12) U.S. provisional patent application serial no. 60/154,047, attorney docket no. 25791.29, filed on 9/16/1999, (13) U.S. provisional patent application serial no. 60/159,082, attorney docket no. 25791.34, filed on 10/12/1999, (14) U.S. provisional patent application serial no. 60/159,039, attorney docket no. 25791.36, filed on 10/12/1999, (15) U.S. provisional patent application serial no. 60/159,033, attorney docket no. 25791.37, filed on 10/12/1999, (16) U.S. provisional patent application serial no. 60/212,359, attorney docket no. 25791.38, filed on 6/19/2000, (17) U.S. provisional patent application serial no. 60/165,228, attorney docket no. 25791.39, filed on 11/12/1999, (18) U.S. provisional patent application serial no. 60/221,443, attorney docket no. 25791.45, filed on 7/28/2000, (19) U.S. provisional patent application serial no. 60/221,645, attorney docket no. 25791.46, filed on 7/28/2000, (20) U.S. provisional patent application serial no. 60/233,638, attorney docket no. 25791.47, filed on 9/18/2000, (21) U.S. provisional patent application serial no. 60/237,334, attorney docket no. 25791.48, filed on 10/2/2000, (22) U.S. provisional patent application serial no. 60/270,007, attorney docket no. 25791.50, filed on 2/20/2001, (23) U.S. provisional patent application serial no. 60/262,434, attorney docket no. 25791.51, filed on 1/17/2001, (24) U.S. provisional patent application serial no. 60/259,486, attorney docket no. 25791.52, filed on 1/3/2001, (25) U.S. provisional patent application serial no. 60/303,740, attorney docket no. 25791.61, filed on 7/6/2001, (26) U.S. provisional patent application serial no. 60/313,453, attorney docket no. 25791.59, filed on 8/20/2001, (27) U.S. provisional patent application serial no. 60/317,985, attorney docket no. 25791.67, filed on 9/6/2001, (28) U.S. provisional patent application serial

no. 60/3318,386, attorney docket no. 25791.67.02, filed on 9/10/2001, (29) U.S. utility patent application serial no. 09/969,922, attorney docket no. 25791.69, filed on 10/3/2001, (30) U.S. utility patent application serial no. 10/016,467, attorney docket no. 25791.70, filed on December 10, 2001, (31) U.S. provisional patent application serial no. 60/343,674, attorney docket no. 25791.68, filed on 12/27/2001; and (32) U.S. provisional patent application serial no. 60/346,309, attorney docket no. 25791.92, filed on 01/07/02, the disclosures of which are incorporated herein by reference. In several alternative embodiments, the expansion device 12 is operated like, or includes operational features of, a conventional commercially available rotary expansion device such, for example, those available from Weatherford International.

**[0063]** In an exemplary embodiment, as illustrated in Fig. 2, the apparatus 10 further includes a lubricant supply 20, and during the operation of the apparatus 10, the lubricant supply injects a lubricating material 22 into an annulus 24 defined between one or more the expansion surfaces 12a of the expansion device 12 and the internal surface 16a of the tubular member 16. In this manner, the amount of energy and/or power required to radially expand and plastically deform the tubular member 16 using the expansion device 12 is reduced. In an exemplary embodiment, the lubricating material 22 includes fluidic and/or solid lubricating materials.

**[0064]** In an exemplary embodiment, as illustrated in Fig. 3, the expansion device 12 of the apparatus 10 further includes an internal lubricant supply 30, and during the operation of the apparatus 10, the lubricant supply injects a lubricating material 32 into the annulus 24. In this manner, the amount of energy and/or power required to radially expand and plastically deform the tubular member 16 using the expansion device 12 is reduced. In an exemplary embodiment, the lubricating material 32 includes fluidic and/or solid lubricating materials. In an exemplary embodiment, the lubricant supply injects the lubricating material 32 into one or more recesses defined in the expansion surface 12a of the expansion device 12.

**[0065]** In an exemplary embodiment, as illustrated in Fig. 4, a layer of a lubricating film 40 is coupled to at least a portion of one or more of the expansion surfaces 12a of the expansion device 12 of the apparatus 10 such that, during the operation of the apparatus, at least a portion of the lubricating film 40 is released into the annulus 24. In this manner, the amount of energy and/or power required to radially expand and plastically deform the tubular member 16 using the expansion device 12 is reduced. In an exemplary embodiment, the lubricating film 40 includes fluidic and/or solid

lubricating materials. In an exemplary embodiment, the thickness and/or composition of the film 40 are non-uniform.

**[0066]** In an exemplary embodiment, as illustrated in Fig. 5, layers 50a and 50b of a lubricating film are coupled to portions of one or more of the expansion surfaces 12a of the expansion device 12 of the apparatus 10 such that, during the operation of the apparatus, at least a portion of the layers of lubricating film, 50a and 50b, are released into the annulus 24. In this manner, the amount of energy and/or power required to radially expand and plastically deform the tubular member 16 using the expansion device 12 is reduced. In an exemplary embodiment, the layers, 50a and 50b, of lubricating film are deposited within recesses, 52a and 52b, respectively, defined within the expansion surface 12a. In an exemplary embodiment, the lubricating film, 50a and 50b, include fluidic and/or solid lubricating materials. In an exemplary embodiment, the thickness and/or composition of the films, 50a and/or 50b, are non-uniform.

**[0067]** In an exemplary embodiment, as illustrated in Figs. 6 and 7, one or more portions of the expansion surfaces 12a of the apparatus 10 define recesses 60a, 60b, 60c, and 60d, that may, for example, contain the lubricant material 22, the lubricant material 32, the lubricant film 40, and/or the lubricant film 50, such that, during the operation of the apparatus, at least a portion of the lubricant materials and/or the lubricant films are released into the annulus 24. In this manner, the amount of energy and/or power required to radially expand and plastically deform the tubular member 16 using the expansion device 12 is reduced. In an exemplary embodiment, the recesses, 60a, 60b, 60c, and 60d, are substantially identical and equally spaced cylindrical cavities defined within the expansion surface 12a of the expansion device. In several alternative embodiments, one or more of the recesses 60 may be different in geometry from one or more of the other recesses 60. In several alternative embodiments, the spacing between the recesses 60 may be unequal.

**[0068]** In an exemplary embodiment, as illustrated in Figs. 8 and 9, one or more portions of the expansion surfaces 12a of the apparatus 10 define recesses 80a, 80b, 80c, and 80d, that may, for example, contain the lubricant material 22, the lubricant material 32, the lubricant film 40, and/or the lubricant film 50, such that, during the operation of the apparatus, at least a portion of the lubricant materials and/or the lubricant films are released into the annulus 24. In this manner, the

amount of energy and/or power required to radially expand and plastically deform the tubular member 16 using the expansion device 12 is reduced. In an exemplary embodiment, the recesses, 80a, 80b, 80c, and 80d, are cylindrical cavities of varying depths defined within the expansion surface 12a of the expansion device. In an exemplary embodiment, the placement of the recesses 80 is such that the pair of recesses, 80a and 80b, are offset from the other pair of recesses, 80c and 80d. In several alternative embodiments, one or more of the recesses 80 may be different in geometry from one or more of the other recesses 80. In several alternative embodiments, the spacing between the recesses 80 may be unequal.

**[0069]** In an exemplary embodiment, as illustrated in Figs. 10 and 11, one or more portions of the expansion surfaces 12a of the apparatus 10 define criss-crossing recesses 100a, 100b, 100c, and 100d, that may, for example, contain the lubricant material 22, the lubricant material 32, the lubricant film 40, and/or the lubricant film 50, such that, during the operation of the apparatus, at least a portion of the lubricant materials and/or the lubricant films are released into the annulus 24. In this manner, the amount of energy and/or power required to radially expand and plastically deform the tubular member 16 using the expansion device 12 is reduced. In an exemplary embodiment, the recesses, 100a and 100b, are substantially parallel to one another, and the recesses, 100c and 100d, are substantially parallel to one another, and the recesses, 100a and 100b, are both substantially orthogonal to the recesses, 100c and 100d. In several alternative embodiments, one or more of the recesses 100 may be different in geometry and orientation from one or more of the other recesses 100. In several alternative embodiments, the spacing between the recesses 100 may be unequal.

**[0070]** In an exemplary embodiment, as illustrated in Fig. 12, one or more portions of the expansion surfaces 12a of the apparatus 10 define recesses 120a, 120b, 120c, 120d, 120e and 120f, that may, for example, contain the lubricant material 22, the lubricant material 32, the lubricant film 40, and/or the lubricant film 50, such that, during the operation of the apparatus, at least a portion of the lubricant materials and/or the lubricant films are released into the annulus 24. In this manner, the amount of energy and/or power required to radially expand and plastically deform the tubular member 16 using the expansion device 12 is reduced. In an exemplary embodiment, the recesses 120 are substantially identical cylindrical recesses that are defined within, and randomly distributed on, the expansion surface 12a of the



expansion device 12. In several alternative embodiments, one or more of the recesses 120 may be different in geometry and orientation from one or more of the other recesses 120.

**[0071]** In an exemplary embodiment, as illustrated in Fig. 13, one or more portions of the expansion surfaces 12a of the apparatus 10 define recesses 130a, 130b, 130c, 130d, 130e and 130f, that may, for example, contain the lubricant material 22, the lubricant material 32, the lubricant film 40, and/or the lubricant film 50, such that, during the operation of the apparatus, at least a portion of the lubricant materials and/or the lubricant films are released into the annulus 24. In this manner, the amount of energy and/or power required to radially expand and plastically deform the tubular member 16 using the expansion device 12 is reduced. In an exemplary embodiment, the recesses 130 are cylindrical recesses that are defined within, and randomly distributed on, the expansion surface 12a of the expansion device 12. In an exemplary embodiment, the volumetric geometry of the recesses 130 are randomly selected.

**[0072]** In an exemplary embodiment, as illustrated in Figs. 14 and 15, one or more portions of the expansion surfaces 12a of the apparatus 10 define one or more recesses 140, that may, for example, contain the lubricant material 22, the lubricant material 32, the lubricant film 40, and/or the lubricant film 50, such that, during the operation of the apparatus, at least a portion of the lubricant materials and/or the lubricant films are released into the annulus 24. In this manner, the amount of energy and/or power required to radially expand and plastically deform the tubular member 16 using the expansion device 12 is reduced. In an exemplary embodiment, the boundaries of the recess 140 include one or more linear and/or non-linear boundaries and the depth of the recess is random in all directions. In several alternative embodiments, one or more of the recesses 140 may be different in geometry and orientation from one or more of the other recesses 140. In several alternative embodiments, the spacing between the recesses 140 may be unequal and/or random. In several alternative embodiments, the depth of the recess 140 may be constant.

**[0073]** In an exemplary embodiment, as illustrated in Figs. 16 and 17, one or more portions of the expansion surfaces 12a of the apparatus 10 define recesses 160a, 160b, 160c, and 160d, that may, for example, contain the lubricant material 22, the lubricant material 32, the lubricant film 40, and/or the lubricant film 50, such that,

during the operation of the apparatus, at least a portion of the lubricant materials and/or the lubricant films are released into the annulus 24. In this manner, the amount of energy and/or power required to radially expand and plastically deform the tubular member 16 using the expansion device 12 is reduced. In an exemplary embodiment, the recesses, 160a, 160b, 160c, and 160d, are substantially identical and equally spaced cylindrical cavities having completely curved walls defined within the expansion surface 12a of the expansion device. In several alternative embodiments, one or more of the recesses 160 are substantially identical in geometry to the dimples found in one or more conventional golf balls. In several alternative embodiments, one or more of the recesses 160 may be different in geometry from one or more of the other recesses 160. In several alternative embodiments, the spacing between the recesses 160 may be unequal.

**[0074]** In an exemplary embodiment, as illustrated in Figs. 18 and 19, one or more portions of the expansion surfaces 12a of the apparatus 10 define a recess 180, that may, for example, contain the lubricant material 22, the lubricant material 32, the lubricant film 40, and/or the lubricant film 50, such that, during the operation of the apparatus, at least a portion of the lubricant materials and/or the lubricant films are released into the annulus 24. In this manner, the amount of energy and/or power required to radially expand and plastically deform the tubular member 16 using the expansion device 12 is reduced. In an exemplary embodiment, the recess 180 is an etched surface having a non-uniform pattern of pits 180a. In several alternative embodiments, the depth of the pits 180a is non-uniform.

**[0075]** In an exemplary embodiment, as illustrated in Figs. 20 and 21, one or more portions of the expansion surfaces 12a of the apparatus 10 define a recess 190, that may, for example, contain the lubricant material 22, the lubricant material 32, the lubricant film 40, and/or the lubricant film 50, such that, during the operation of the apparatus, at least a portion of the lubricant materials and/or the lubricant films are released into the annulus 24. In this manner, the amount of energy and/or power required to radially expand and plastically deform the tubular member 16 using the expansion device 12 is reduced. In an exemplary embodiment, the recess 190 is a knurled surface having a uniform pattern of pits 190a. In several alternative embodiments, the pattern of the pits 190a and/or the depth of the pits 190a is non-uniform.

**[0076]** In an exemplary embodiment, as illustrated in Fig. 22, during the operation of the apparatus 10, the interface between the expansion surface 12a of the expansion device 12 and the interior surface 16a of the tubular member 16 includes a leading edge portion 220 and a trailing edge portion 222. In an exemplary embodiment, as illustrated in Fig. 23, the concentration of lubrication is increased in the leading and trailing edge portions, 220 and 222, respectively, in order to reduce the amount of energy and/or power required to radially expand and plastically deform the tubular member 16 using the expansion device 12.

**[0077]** In several exemplary embodiments, the concentration of lubrication within a specific portions of the expansion surface 12a of the expansion device 12 is increased by increasing one or more of the following: 1) the flow of the lubricant materials 22 and/or 32 into the annulus 24 surrounding the specific portion; 2) the volume of the films 40 and/or 50 applied to the specific portion; 3) the density of the recesses 60, 80, 100, 120, 130, 140, 160, 180, and/or 200 within the specific portion; and/or 4) the normalized oil volume within the specific portion.

**[0078]** In an exemplary embodiment, as illustrated in Fig. 24, during the operation of the apparatus 10, recesses, 240a and 240b, defined within the expansion surface 12a of the expansion device 12, provide a support for, and define lubrication ball bearings, 242a and 242b, for lubricating the interface between the expansion surface of the expansion device and the internal surface 16a of the tubular member. In this manner, the lubricating materials derived from one or more of the following: the lubricant materials 22 and/or 32 and/or the films 40 and/or 50 are formed into a ball-like fluidic lubricating structure that act like lubricating ball bearings thereby reducing the amount of energy and/or power required to radially expand and plastically deform the tubular member 16 using the expansion device 12.

**[0079]** In an exemplary embodiment, during the operation of the apparatus 10, the rate of strain of the tubular member 16 varies as a function of the geometry of the expansion surface 12a of the expansion device. Thus, for example, certain portions of the tubular member 16 that interface with the expansion surface 12a of the expansion device 12 may experience rates of strain that are different from other portions of the tubular member that interface with the expansion surface of the expansion device. In an exemplary embodiment, during the operation of the apparatus 10, the concentration of lubrication is increased in those areas having greater rates of strain as compared with those areas having lesser rates of strain in

order to reduce the amount of energy and/or power required to radially expand and plastically deform the tubular member 16 using the expansion device 12. In an exemplary embodiment, as illustrated in Fig. 25, the relationship between the concentration of lubrication and the rate of strain is a linear relationship. In an alternative embodiment, as illustrated in Fig. 26, the relationship between the concentration of lubrication and the rate of strain is a non-linear relationship having a decreasing slope with increasing rate of strain. In an alternative embodiment, as illustrated in Fig. 27, the relationship between the concentration of lubrication and the rate of strain is a non-linear relationship having an decreasing slope with increasing rate of strain. In an alternative embodiment, as illustrated in Fig. 28, the relationship between the concentration of lubrication and the rate of strain includes one or more step functions. In an alternative embodiment, as illustrated in Fig. 29, the relationship between the concentration of lubrication and the rate of strain includes one or more of the characteristics of Figs. 25-28.

**[0080]** In several exemplary embodiments, the concentration of lubrication within a specific portions of the expansion surface 12a of the expansion device 12 is increased by increasing one or more of the following: 1) the flow of the lubricant materials 22 and/or 32 into the annulus 24 surrounding the specific portion; 2) the volume of the films 40 and/or 50 applied to the specific portion; 3) the density of the recesses 60, 80, 100, 120, 130, 140, 160, 180, and/or 200 within the specific portion; and/or 4) the normalized oil volume within the specific portion.

**[0081]** More generally, in several exemplary embodiments, the concentration of lubrication within a specific portions of the expansion surface 12a of the expansion device 12 is controlled by adjusting one or more of the following: 1) the flow of the lubricant materials 22 and/or 32 into the annulus 24 surrounding the specific portion; 2) the volume of the films 40 and/or 50 applied to the specific portion; 3) the density of the recesses 60, 80, 100, 120, 130, 140, 160, 180, and/or 200 within the specific portion; and/or 4) the normalized oil volume within the specific portion.

**[0082]** In several exemplary embodiments, during at least a portion of the operation of the apparatus 10, at least portions of the annulus 24 between the expansion surface 12a of the expansion device 12 and the internal surface 16a of the tubular member 16 may be reduced in thickness to zero thereby permitting the at least a portion of the expansion surface of the expansion device to contact at least a portion of the interior surface of the tubular member.

**[0083]** In several exemplary embodiments, the lubricating films 40 and/or 50 include a physical vapor deposition Chromium Nitride coating commercially available from Phygen, Inc. in Minneapolis, Minnesota. In several exemplary embodiments, the lubricating films 40 and/or 50 are coupled to an expansion surface 12a fabricated from DC53 steel, new cold die steel, commercially available from Daido Steel Co. in Japan and/or International Steel Co., in Florence, Kentucky.

**[0084]** In several exemplary embodiments, the surface texture of at least a portion of one or more of the expansion surfaces 12a and/or one or more of the recesses 60, 80, 100, 120, 140, 160, 180, 200 and/or 240 is provided by polishing a surface roughness into the expansion surfaces and/or recesses using commercially available methods and apparatus available from REM Chemicals, in Brenham, Texas.

**[0085]** In several exemplary embodiments, the lubricant materials 22 and/or 32 include various environmentally friendly lubricant materials commercially available from Oleon, Inc. in Belgium and/or as lubricant materials # 2633-179 - 1, 2, 3, 4, 5, and 6 from Houghton International, Valley Forge, Pennsylvania. In several exemplary embodiments, the lubricant materials 22 and/or 32 include Radiagreen eme salt.

**[0086]** Referring to Fig. 30, in an exemplary embodiment, at least a portion of one or more of the expansion surfaces 12a of the expansion device 12 is textured and a lubricating film 300 is coupled to at least a portion of the textured expansion surface. Furthermore, in an exemplary embodiment, at least a portion of the interior surface 16a of the tubular member 16 includes a lubricating film 302, and an annulus 304 defined between the expansion device 12 and the tubular member 16 includes a lubricant material 306. In an exemplary embodiment, the lubricating film 300 is harder and more resistant to abrasion than the lubricating film 302. In an exemplary embodiment, the use of a textured expansion surface 12a, the lubricating film 300, the lubricating film 302, and the lubricant film 306 during the operation of the apparatus 10 provided a friction coefficient less than about 0.02. In an exemplary embodiment, the textured expansion surface 12a is provided using one or more of the recesses 60, 80, 100, 120, 140, 160, 180, 200 and/or 240 described above and/or by texturing the expansion surface 12a. In an exemplary embodiment, the expansion surface 12a is fabricated from a DC53 tool steel, commercially available from Daido Steel in Japan, the texturing of the expansion surface 12a is provided by polishing the expansion surface using the commercially available products and

services of REM Chemicals in Brenham, Texas, the lubricating film 300 includes a hard film Phygen 2, physical vapor deposition Chromium Nitride coating, commercially available from Phygen, Inc., in Minneapolis, MN, the lubricating film 302 includes a Polytetrafluoroethylene (PTFE) based soft film coating, commercially available as a Brighton 9075 coating from Brighton Laboratories, in Howell, Michigan, and the lubricant material 306 includes a commercially available lubricant from Houghton International, in Valley Forge, Pennsylvania.

**[0087]** In an exemplary embodiment, the surface texture of the expansion surface 12a and/or one or more of the recesses 60, 80, 100, 120, 140, 160, 180, 200 and/or 240 is characterized by one or more of the following parameters:  $R_a$ ,  $R_q$ ,  $R_{sk}$ ,  $R_{ku}$ ,  $R_p$ ,  $R_v$ ,  $R_l$ ,  $R_{pm}$ ,  $R_{vm}$ ,  $R_z$ ,  $R_{pk}$ ,  $R_k$ ,  $R_{vk}$ ,  $M_{r1}$ ,  $M_{r2}$ ,  $R_{pk}/R_k$ ,  $R_{vk}/R_k$ ,  $R_{pk}/R_{vk}$ , X Slope  $R_q$ , Y Slope  $R_q$ , NVOL, and/or SAI. In an exemplary embodiment, the measurement of these parameters is provided using the commercially available services of Michigan Metrology LLC in Livonia, Michigan.

**[0088]**  $R_a$  refers to the arithmetic average of the absolute values of the surface height deviations measured from the best fitting plane, cylinder or sphere.  $R_a$  is described by:

$$R_a = \frac{1}{A} \iint_A |Z(x, y)| dx dy$$

where  $Z(x, y)$  = the vertical position of a position on the surface at coordinates  $x$  and  $y$

**[0089]**  $R_q$  refers to the RMS (Standard Deviation) or "first moment" of the height distribution, as described by:

$$R_q = \sqrt{\frac{1}{A} \iint_A (Z(x, y))^2 dx dy}$$

**[0090]**  $R_{sk}$  refers to the skew or "second moment" of the height distribution., as described by:

$$R_{sk} = \frac{1}{R_q^3} \iint_A (Z(x, y))^3 dx dy$$

**[0091]**  $R_{ku}$  refers to the "kurtosis" or the "third moment" of the height distribution, described by:

$$R_{ku} = \frac{1}{R_q^4} \iint_A (Z(x, y))^4 dx dy$$

**[0092]**  $R_p$ ,  $R_v$ , and  $R_l$  are parameters evaluated from the absolute highest and lowest points found on the surface.  $R_p$  is the height of the highest point,  $R_v$  is the depth of the lowest point and  $R_l$  is found from  $R_p - R_v$ . The  $R_{pm}$ ,  $R_{vm}$ , and  $R_z$  parameters

are evaluated from an average of the heights and depths of the extreme peaks and valleys.  $R_{pm}$  is found by averaging the heights of the ten (10) highest peaks found over the complete 3D image.  $R_{vm}$  is found by averaging the depths of the ten (10) lowest valleys found over the complete 3D image.  $R_z$  is then found by  $(R_{pm}-R_{vm})$ .

**[0093]** The parameters  $R_{pk}$ ,  $R_k$ ,  $R_{vk}$ ,  $Mr_1$ , and  $Mr_2$  are all derived from the bearing ratio curve based on the DIN 4776 standard, the disclosure of which is incorporated herein by reference. The bearing area curve is a measure of the relative cross-sectional area a plane passing through the measured surface, from the highest peak to the lowest valley, would encounter.  $R_{pk}$  is a measure of the peak height above the nominal/core roughness.  $R_k$  is a measure of the nominal or "core" roughness ("peak to valley") of the surface.  $R_{vk}$  is a measure of the valley depth below the nominal /core roughness.  $Mr_1$ , the peak material ratio, indicates the percentage of material that comprise the peak structures associate with  $R_{pk}$ .  $Mr_2$  is a measure of the valley material ratio, with  $(100\%-Mr_2)$  representing the percentage of material that comprise the valley structures associated with  $R_{vk}$ .

**[0094]**  $R_{pk}/R_k$ ,  $R_{vk}/R_k$ ,  $R_{pk}/R_{vk}$ : the ratios of the various bearing ratio parameters may be helpful in further understanding the nature of a particular surface texture. In some instances two surfaces with indistinguishable average roughness ( $R_a$ ) may be easily distinguished by the ratio such as  $R_{pk}/R_k$ . For example, a surface with high peaks as opposed to a surface with deep valleys may have the same  $R_a$  but with vastly different  $R_{pk}/R_k$  values.

**[0095]** X Slope  $R_q$ , Y Slope  $R_q$ : The parameters X Slope  $R_q$  and Y Slope  $R_q$  are found by calculating the Standard Deviation (i.e. RMS or  $R_q$ ) of the slopes of the surface along the X and Y directions respectively. The slope is found by taking the derivative of the surface profiles along each direction, using the lateral resolution of the measurement area as the point spacing. Analytically, X Slope  $R_q$  and Y Slope  $R_q$  are given by:

$$X \text{ Slope } R_q = \left( \iint_a \left( \frac{\partial Z(x,y)}{\partial x} - \left\langle \frac{\partial Z(x,y)}{\partial x} \right\rangle \right)^2 dx dy \right)^{1/2} \quad Y \text{ Slope } R_q = \left( \iint_a \left( \frac{\partial Z(x,y)}{\partial y} - \left\langle \frac{\partial Z(x,y)}{\partial y} \right\rangle \right)^2 dx dy \right)^{1/2}$$

Where the brackets,  $\langle \rangle$ , represent the average value of all slopes in the relevant direction

**[0096]** NVOL: The Normalized Volume (NVOL) of the surface is found by calculating the volume contained by the surface and a "plane" that is placed near the top of the surface. The placement of the reference plane is typically done on a statistical basis

to assure that the very high peak locations are not used as the reference point for the plane. Once the volume is calculated (e.g. in units of  $\text{cm}^3$ ), the result is "normalized" to the cross sectional area of the plane (i.e. units of  $\text{m}^2$ ). Other units of NVOL are BCM, which is an acronym for "Billions of Cubic Microns per Inch Squared".

**[0097]** The Surface Area Index (SAI) evaluates the surface area at the lateral resolution of the measured surface as compared to that of a perfectly flat/smooth surface. The calculation involves fitting triangular patches between the measured points and adding up the total area of all patches. A ratio is then formed of the total surface area measured and the nominal flat area of measurement. This analysis is a precursor to a complete fractal analysis of the surface. Since SAI is a ratio, it is a unit-less quantity.

**[0098]** In an exemplary embodiment, one or more of the parameters  $R_a$ ,  $R_q$ ,  $R_{sk}$ ,  $R_{ku}$ ,  $R_p$ ,  $R_v$ ,  $R_t$ ,  $R_{pm}$ ,  $R_{vm}$ ,  $R_z$ ,  $R_{pk}$ ,  $R_k$ ,  $R_{vk}$ ,  $M_{r1}$ ,  $M_{r2}$ ,  $R_{pk}/R_k$ ,  $R_{vk}/R_k$ ,  $R_{pk}/R_{vk}$ , X Slope  $R_q$ , Y Slope  $R_q$ , NVOL, and/or SAI described above are defined as described at the following website: <http://www.michmet.com>, the disclosure of which is incorporated herein by reference.

**[0099]** In an exemplary implementation, an apparatus 10 having an expansion device 12 including an expansion surface 12a fabricated from conventional D2 steel was operated to expand a plurality of tubular members 16 fabricated from low carbon steel using a water base mud media as a lubricating material. Fig. 31a is top view of a portion of the expansion surface 12a of the expansion device 12 of the apparatus after repeated radial expansions and plastic deformations of the tubular members 16 using the apparatus 10. Fig. 31b is a magnified perspective view of the portion of the expansion surface 12a of the expansion device 12 of the apparatus after repeated radial expansions and plastic deformations of the tubular members 16 using the apparatus 10. Fig. 31c is a graphical illustration of the surface profile of a sliced portion of the portion of the expansion surface 12a of the expansion device 12 of the apparatus after repeated radial expansions and plastic deformations of the tubular members 16 using the apparatus 10. Fig. 31d is a graphical and tabular illustration of the bearing ratio,  $R_a$ ,  $R_z$ ,  $R_{pk}$ ,  $R_k$ ,  $R_{vk}$ , Sty X Pc (X Slope  $R_q$ ), Sty Y Pc (Y Slope  $R_q$ ), and NVOL for the portion of the expansion surface 12a of the expansion device 12 of the apparatus after repeated radial expansions and plastic deformations of the tubular members 16 using the apparatus 10. As illustrated in



Fig. 31d, the exemplary implementation had the following characteristics:

Parameter	Value
$R_a$	277.930 nm
$R_z$	3.13 nm
$R_{pk}$	377.167 nm
$R_k$	829.31 nm
$R_{vk}$	216.287 nm
Slope $R_q$	3.88/mm
Y Slope $R_q$	6.13/mm
NVOL	0.822 BCM

In the exemplary implementation of the embodiment of Figs. 31a, 31b, 31c, and 31d, the forces required to overcome friction during the operation of the apparatus 10 were about 45% of all the expansion forces required to radially expand and plastically deform the tubular member 16 and the coefficient of friction for the interface between the expansion surfaces 12a of the expansion device 12 and the interior surface 16a of the tubular member was about 0.125.

**[00100]** In an exemplary implementation, an apparatus 10 having an expansion device 12 including an expansion surface 12a fabricated from DC53 tool steel, available from Daido Steel in Japan, was operated to expand a plurality of tubular members 16 fabricated from low carbon steel. The expansion surface 12a was surface polished using the services of REM Chemicals in Brenham, Texas and a lubricating film including a Chromium Nitride coating, available from Phygen, Inc., in Minneapolis, Minnesota, was coupled to the expansion surface. Fig. 32a is top view of a portion of the expansion surface 12a of the expansion device 12 of the apparatus after repeated radial expansions and plastic deformations of the tubular members 16 using the apparatus 10. Fig. 32b is a magnified perspective view of the portion of the expansion surface 12a of the expansion device 12 of the apparatus after repeated radial expansions and plastic deformations of the tubular members 16 using the apparatus 10. Fig. 32c is a graphical illustration of the surface profile of a sliced portion of the portion of the expansion surface 12a of the expansion device 12 of the apparatus after repeated radial expansions and plastic deformations of the tubular members 16 using the apparatus 10. Fig. 32d is a graphical and tabular illustration of the bearing ratio,  $R_a$ ,  $R_z$ ,  $R_{pk}$ ,  $R_k$ ,  $R_{vk}$ , Sty X Pc (X Slope  $R_q$ ), Sty Y Pc

(Y Slope  $R_q$ ), and NVOL for the portion of the expansion surface 12a of the expansion device 12 of the apparatus after repeated radial expansions and plastic deformations of the tubular members 16 using the apparatus 10. As illustrated in Fig. 32d, the exemplary implementation had the following characteristics:

Parameter	Value
$R_a$	60.205 nm
$R_z$	1.99 nm
$R_{pk}$	25.009 nm
$R_k$	152.12 nm
$R_{vk}$	92.963 nm
Slope $R_q$	2.21/mm
Y Slope $R_q$	3.53/mm
NVOL	0.047 BCM

In the exemplary implementation of the embodiment of Figs. 32a, 32b, 32c, and 32d, the forces required to overcome friction during the operation of the apparatus 10 were between about 30% to 8% of all the expansion forces required to radially expand and plastically deform the tubular member 16 and the coefficient of friction for the interface between the expansion surfaces 12a of the expansion device 12 and the interior surface 16a of the tubular member was about 0.06. Furthermore, in the exemplary embodiment of Figs. 32a, 32b, 32c, and 32d, the bearing ratio of the expansion surface 12a of the expansion device 12 was greater than 75% on 60% of the  $R_z$  surface roughness.

**[00101]** A comparison of the exemplary implementation illustrated in Figs. 31a, 31b, 31c, and 31d and the exemplary implementation illustrated in Figs. 32a, 32b, 32c, and 32d indicated that an example of a preferred surface texture for an expansion surface 12a of the expansion device 12 during the radial expansion and plastic deformation of the tubular member 16 was a surface texture having a plateau-like surface with relatively deep recesses as provided in the exemplary implementation of Figs. 32a, 32b, 32c, and 32d. This was an unexpected result.

**[00102]** Furthermore, a comparison of the exemplary implementation illustrated in Figs. 31a, 31b, 31c, and 31d and the exemplary implementation illustrated in Figs. 32a, 32b, 32c, and 32d also indicated that the expansion surface of the exemplary implementation illustrated in Figs. 32a, 32b, 32c, and 32d provided not only a

smoother surface, as measured by  $R_a$  and/or  $R_z$ , but also provided much higher load capacity, as measured by the bearing ratio. Furthermore, the bearing ratio for the exemplary implementation illustrated in Figs. 32a, 32b, 32c, and 32d had much less variation in value than the bearing ratio for the exemplary implementation illustrated in Figs. 31a, 31b, 31c, and 31d. Thus, in a preferred embodiment, the bearing ratio varies less than about 15% across the expansion surface 12a. In addition, the exemplary implementation illustrated in Figs. 32a, 32b, 32c, and 32d provided a bearing ratio about double that of the exemplary implementation illustrated in Figs. 31a, 31b, 31c, and 31d. For example, at the level of 60%  $R_z$ , the percentage of the material supporting a load on the exemplary implementation illustrated in Figs. 32a, 32b, 32c, and 32d was about 80% in comparison to about 37% for the exemplary implementation illustrated in Figs. 31a, 31b, 31c, and 31d.

**[00103]** In an exemplary embodiment, the preferred surface texture of the exemplary implementation of Figs. 32a, 32b, 32c, and 32d, a plateau-like surface with relatively deep recesses, is provided by laser dimpling the expansion surface 12a.

**[00104]** In an exemplary embodiment, as illustrated in Fig. 33, the apparatus 10 provides a tribological system 330 including the expansion device 12, the tubular member 16, and one or more lubricating elements 332 such as, for example, those elements described above for reducing friction between the expansion surfaces 12a of the expansion device and the tubular member during the operation of the apparatus 10. In an exemplary embodiment, the system 330 is designed and operated to minimize the friction between the expansion device 12 and the tubular member 16.

**[00105]** An expansion cone for radially expanding multiple tubular members has been described that includes a body having an annular outer peripheral surface, and at least a portion of the surface being textured with friction reducing reliefs recessed into the surface. In an exemplary embodiment, the surface includes a knurled surface. In an exemplary embodiment, the surface includes a laser dimpled surface. In an exemplary embodiment, the surface includes a pitted and sprayed surface. In an exemplary embodiment, the body includes the pitted surface formed of a first material, the pitted surface being sprayed with a second friction reducing material and the sprayed surface being partially removed sufficient to expose some

of the first and second materials. In an exemplary embodiment, the surface includes an etched surface.

**[00106]** A method for radially expanding a tubular member has been described that includes providing a tubular member having an inside diameter, providing an expansion cone having an annular outer peripheral surface including a diameter greater than the inside diameter of the tubular member, texturing the outer peripheral surface with friction reducing reliefs recessed into the surface, and moving the expansion cone axially through the tubular member for radially expanding and plastically deforming the tubular member. In an exemplary embodiment, the surface includes a knurled surface. In an exemplary embodiment, the surface includes a laser dimpled surface. In an exemplary embodiment, the surface includes a pitted and sprayed surface. In an exemplary embodiment, the method further includes pitting the outer peripheral surface, spraying the surface, and grinding the surface to expose both an original portion of the surface and a sprayed portion of the surface. In an exemplary embodiment, the surface includes an etched surface.

**[00107]** A reduced friction radial expansion apparatus has been described that includes a plurality of tubular members having an axial passage formed therethrough including an inside diameter, an expansion cone having an annular outer peripheral surface including an outside diameter greater than the inside diameter of the axial passage, and at least a portion of the outer peripheral surface being textured with friction reducing reliefs recessed into the surface. In an exemplary embodiment, the surface includes a knurled surface. In an exemplary embodiment, the surface includes a laser dimpled surface. In an exemplary embodiment, the surface includes a pitted and sprayed surface. In an exemplary embodiment, the cone includes a pitted surface formed of a first material, the pitted surface being sprayed with a second friction reducing material and the sprayed surface being partially removed sufficient to expose some of the first and second materials. In an exemplary embodiment, the surface includes an etched surface. In an exemplary embodiment, a low friction material includes deposited in the reliefs. In an exemplary embodiment, the outer peripheral surface includes a flush surface including a combination of portions of material of the expansion cone and portions of a low friction material deposited in the reliefs.

**[00108]** An apparatus for radially expanding and plastically deforming a tubular member has been described that includes a support member, an expansion device

coupled to an end of the support member comprising one or more expansion surfaces for engaging the tubular member during the radial expansion and plastic deformation of the tubular member, and a lubrication system for lubricating an interface between one or more of the expansion surfaces of the expansion device and one or more interior surfaces of the tubular member. In an exemplary embodiment, the lubrication system includes a supply of a lubricant, and an injector for injecting the lubricant into the interface. In an exemplary embodiment, the supply of lubricant is provided within the expansion device. In an exemplary embodiment, one or more of the expansion surfaces define one or more recesses, and one or more of the recesses are coupled to the injector. In an exemplary embodiment, the lubrication system includes a lubricating film coupled to one or more of the expansion surfaces. In an exemplary embodiment, one or more of the expansion surfaces define one or more recesses, and at least a portion of the lubricating film is deposited within one or more of the recesses. In an exemplary embodiment, one or more of the expansion surfaces of the expansion device define one or more recesses. In an exemplary embodiment, at least some of the recesses are identical to one another. In an exemplary embodiment, at least some of the recesses are equally spaced from one another. In an exemplary embodiment, a depth dimension of the recesses are non-uniform. In an exemplary embodiment, at least some of the recesses intersect. In an exemplary embodiment, the location of at least some of the recesses is randomly distributed. In an exemplary embodiment, the geometry of at least some of the recesses is randomly distributed. In an exemplary embodiment, a surface texture of at least some of the recesses is randomly distributed. In an exemplary embodiment, the geometry of at least some of the recesses is linear. In an exemplary embodiment, the geometry of at least some of the recesses is non-linear. In an exemplary embodiment, the interface includes a leading edge portion and a trailing edge portion, and the lubrication system provides a higher lubrication concentration in at least one of the leading and trailing edge portions. In an exemplary embodiment, one or more of the expansion surfaces of the expansion device define one or more recesses, and the apparatus further includes one or more lubricating ball bearings supported within at least one of the recesses. In an exemplary embodiment, a lubrication concentration provided by the lubrication system is varied as a function of a rate of strain of the tubular member during an operation of the apparatus. In an exemplary embodiment, the function includes a

linear function. In an exemplary embodiment, the function includes a non-linear function. In an exemplary embodiment, the function includes a step function.

**[00109]** A method for radially expanding and plastically deforming a tubular member has been described that includes radially expanding and plastically deforming the tubular member using an expansion device comprising one or more expansion surfaces, and lubricating an interface between one or more of the expansion surfaces of the expansion device and one or more interior surfaces of the tubular member. In an exemplary embodiment, the method further includes injecting a supply of lubricant into the interface. In an exemplary embodiment, the supply of lubricant is provided within the expansion device. In an exemplary embodiment, one or more of the expansion surfaces define one or more recesses, and the method further comprises injecting the supply of lubricant into one or more of the recesses. In an exemplary embodiment, the method further includes coupling a lubricating film to one or more of the expansion surfaces. In an exemplary embodiment, one or more of the expansion surfaces define one or more recesses, and at least a portion of the lubricating film is coupled to one or more of the recesses. In an exemplary embodiment, one or more of the expansion surfaces of the expansion device define one or more recesses. In an exemplary embodiment, at least some of the recesses are identical to one another. In an exemplary embodiment, at least some of the recesses are equally spaced from one another. In an exemplary embodiment, a depth dimension of the recesses are non-uniform. In an exemplary embodiment, at least some of the recesses intersect. In an exemplary embodiment, the location of at least some of the recesses is randomly distributed. In an exemplary embodiment, the geometry of at least some of the recesses is randomly distributed. In an exemplary embodiment, a surface texture of at least some of the recesses is randomly distributed. In an exemplary embodiment, the geometry of at least some of the recesses is linear. In an exemplary embodiment, the geometry of at least some of the recesses is non-linear. In an exemplary embodiment, the interface includes a leading edge portion and a trailing edge portion, and the method further includes providing a higher lubrication concentration in at least one of the leading and trailing edge portions. In an exemplary embodiment, one or more of the expansion surfaces of the expansion device define one or more recesses, and the method further comprises forming one or more lubricating ball bearings within at least one of the recesses. In an exemplary embodiment, the method further includes varying a

lubrication concentration as a function of a rate of strain of the tubular member during the radial expansion and plastic deformation of the tubular member. In an exemplary embodiment, the function includes a linear function, a non-linear function, and/or a step function.

**[00110]** A system for lubricating an interface between an expansion device and a tubular member during a radial expansion of the tubular member by the expansion device has been described that includes means for supplying a quantity of a lubricant material, and means for injecting at least a portion of the lubricant material into the interface. In an exemplary embodiment, the system further includes means for varying the concentration of the lubricant material within the interface.

**[00111]** A method of operating a system for lubricating an interface between an expansion device and a tubular member during a radial expansion of the tubular member by the expansion device has been described that includes determining a rate of strain of the tubular member during an operation of the expansion device, and varying a concentration of a lubricant material within the interface during the operation of the expansion device as a function of the determined rate of strain.

**[00112]** A method of operating a system for lubricating an interface between an expansion device and a tubular member during a radial expansion of the tubular member by the expansion device has been described that includes determining one or more characteristics of the interface during an operation of the expansion device, and varying a concentration of a lubricant material within the interface during the operation of the expansion device as a function of one or more of the determined characteristics.

**[00113]** A system for lubricating an interface between an expansion device and a tubular member during a radial expansion of the tubular member by the expansion device has been described that includes means for determining a rate of strain of the tubular member during an operation of the expansion device, and means for varying a concentration of a lubricant material within the interface during the operation of the expansion device as a function of the determined rate of strain.

**[00114]** A system for lubricating an interface between an expansion device and a tubular member during a radial expansion of the tubular member by the expansion device has been described that includes means for determining one or more characteristics of the interface during an operation of the expansion device, and means for varying a concentration of a lubricant material within the interface during

the operation of the expansion device as a function of one or more of the determined characteristics.

**[00115]** A method of operating a system for lubricating an interface between an expansion device and a tubular member during a radial expansion of the tubular member by the expansion device has been described that includes determining one or more characteristics of the operation of the expansion device, and varying a concentration of a lubricant material within the interface during the operation of the expansion device as a function of one or more of the determined characteristics.

**[00116]** A system for lubricating an interface between an expansion device and a tubular member during a radial expansion of the tubular member by the expansion device has been described that includes means for determining one or more characteristics of the operation of the expansion device, and means for varying a concentration of a lubricant material within the interface during the operation of the expansion device as a function of one or more of the determined characteristics.

**[00117]** A tribological system for lubricating an interface between an expansion device and a tubular member during a radial expansion and plastic deformation of the tubular member, has been described that includes an expansion surface coupled to the expansion device defining a surface texture, a first lubricating film coupled to the expansion surface, a second lubricating film coupled to an interior surface of the tubular member, and a lubricating material disposed within an annulus defined between the expansion surface of the expansion device and the interior surface of the tubular member. In an exemplary embodiment, a resistance to abrasion of the first lubricating film is greater than a resistance to abrasion of the second lubricating film. In an exemplary embodiment, the  $R_a$  for the expansion surface is less than or equal to 60.205 nm. In an exemplary embodiment, the  $R_z$  for the expansion surface is less than or equal to 1.99 nm. In an exemplary embodiment, the  $R_a$  for the expansion surface is about 60.205 nm. In an exemplary embodiment, the  $R_z$  for the expansion surface is about 1.99 nm. In an exemplary embodiment, the  $R_a$  for the expansion surface is less than or equal to 277.930 nm. In an exemplary embodiment, the  $R_z$  for the expansion surface is less than or equal to 3.13 nm. In an exemplary embodiment, the  $R_a$  for the expansion surface is less than or equal to 277.930 nm and greater than or equal to 60.205 nm. In an exemplary embodiment, the  $R_z$  for the expansion surface is less than or equal to 3.13 nm and greater than or equal to 1.99 nm. In an exemplary embodiment, the expansion surface includes a



plateau-like surface that defines one or more relatively deep recesses. In an exemplary embodiment, the first lubricating film includes chromium nitride. In an exemplary embodiment, the second lubricating film includes PTFE. In an exemplary embodiment, the expansion surface includes DC53 tool steel. In an exemplary embodiment, the coefficient of friction for the interface is less than or equal to 0.125. In an exemplary embodiment, the coefficient of friction for the interface is less than 0.125. In an exemplary embodiment, the coefficient of friction for the interface is less than or equal to 0.06. In an exemplary embodiment, the coefficient of friction for the interface is less than 0.06. In an exemplary embodiment, the expansion surface includes a polished surface. In an exemplary embodiment, the forces required to overcome friction during the radial expansion and plastic deformation of the tubular member are less than or equal to 45% of the total forces required to radially expand and plastically deform the tubular member. In an exemplary embodiment, the forces required to overcome friction during the radial expansion and plastic deformation of the tubular member are less than 45% of the total forces required to radially expand and plastically deform the tubular member. In an exemplary embodiment, the forces required to overcome friction during the radial expansion and plastic deformation of the tubular member are less than or equal to 8% of the total forces required to radially expand and plastically deform the tubular member. In an exemplary embodiment, the forces required to overcome friction during the radial expansion and plastic deformation of the tubular member are less than 8% of the total forces required to radially expand and plastically deform the tubular member. In an exemplary embodiment, the bearing ratio of the expansion surface varies less than about 15%. In an exemplary embodiment, the bearing ratio of the expansion surface of the expansion device is greater than 75% on 60% of the  $R_z$  surface roughness.

**[00118]** A method of lubricating an interface between an expansion surface of an expansion device and a tubular member during a radial expansion and plastic deformation of the tubular member has been described that includes texturing the expansion surface, coupling a first lubricating film coupled to the expansion surface, coupling a second lubricating film to an interior surface of the tubular member, and disposing a lubricating material within an annulus defined between the expansion surface of the expansion device and the interior surface of the tubular member. In an exemplary embodiment, a resistance to abrasion of the first lubricating film is greater than a resistance to abrasion of the second lubricating film. In an exemplary

embodiment, the  $R_a$  for the expansion surface is less than or equal to 60.205 nm. In an exemplary embodiment, the  $R_z$  for the expansion surface is less than or equal to 1.99 nm. In an exemplary embodiment, the  $R_a$  for the expansion surface is about 60.205 nm. In an exemplary embodiment, the  $R_z$  for the expansion surface is about 1.99 nm. In an exemplary embodiment, the  $R_a$  for the expansion surface is less than or equal to 277.930 nm. In an exemplary embodiment, the  $R_z$  for the expansion surface is less than or equal to 3.13 nm. In an exemplary embodiment, the  $R_a$  for the expansion surface is less than or equal to 277.930 nm and greater than or equal to 60.205 nm. In an exemplary embodiment, the  $R_z$  for the expansion surface is less than or equal to 3.13 nm and greater than or equal to 1.99 nm. In an exemplary embodiment, the expansion surface includes a plateau-like surface that defines one or more relatively deep recesses. In an exemplary embodiment, the first lubricating film includes chromium nitride. In an exemplary embodiment, the second lubricating film includes PTFE. In an exemplary embodiment, the expansion surface includes DC53 tool steel. In an exemplary embodiment, the coefficient of friction for the interface is less than or equal to 0.125. In an exemplary embodiment, the coefficient of friction for the interface is less than 0.125. In an exemplary embodiment, the coefficient of friction for the interface is less than or equal to 0.06. In an exemplary embodiment, the coefficient of friction for the interface is less than 0.06. In an exemplary embodiment, the expansion surface includes a polished surface. In an exemplary embodiment, the forces required to overcome friction during the radial expansion and plastic deformation of the tubular member are less than or equal to 45% of the total forces required to radially expand and plastically deform the tubular member. In an exemplary embodiment, the forces required to overcome friction during the radial expansion and plastic deformation of the tubular member are less than 45% of the total forces required to radially expand and plastically deform the tubular member. In an exemplary embodiment, the forces required to overcome friction during the radial expansion and plastic deformation of the tubular member are less than or equal to 8% of the total forces required to radially expand and plastically deform the tubular member. In an exemplary embodiment, the forces required to overcome friction during the radial expansion and plastic deformation of the tubular member are less than 8% of the total forces required to radially expand and plastically deform the tubular member. In an exemplary embodiment, the bearing ratio of the expansion surface varies less than about 15%. In an exemplary

embodiment, the bearing ratio of the expansion surface of the expansion device is greater than 75% on 60% of the  $R_z$  surface roughness.

**[00119]** A system for radially expanding and plastically deforming a tubular member has been described in which the amount of energy required to overcome frictional forces during the radial expansion and plastic deformation of the tubular member is less than or equal to 45% of the total amount of energy required to radially expand and plastically deform the tubular member.

**[00120]** A system for radially expanding and plastically deforming a tubular member has been described that includes an expansion device, wherein the coefficient of friction between the expansion device and the tubular member during the radial expansion and plastic deformation of the tubular member is less than or equal to 0.125.

**[00121]** A system for radially expanding and plastically deforming a tubular member has been described in which the amount of energy required to overcome frictional forces during the radial expansion and plastic deformation of the tubular member is less than or equal to 8% of the total amount of energy required to radially expand and plastically deform the tubular member.

**[00122]** A system for radially expanding and plastically deforming a tubular member has been described that includes an expansion device, wherein the coefficient of friction between the expansion device and the tubular member during the radial expansion and plastic deformation of the tubular member is less than or equal to 0.06.

**[00123]** A tribological system for lubricating an interface between an expansion device and a tubular member during a radial expansion and plastic deformation of the tubular member has been described that includes an expansion surface coupled to the expansion device defining a surface texture, a first lubricating film coupled to the expansion surface, and a second lubricating film coupled to an interior surface of the tubular member, wherein a resistance to abrasion of the first lubricating film is greater than a resistance to abrasion of the second lubricating film.

**[00124]** A tribological system for lubricating an interface between an expansion device and a tubular member during a radial expansion and plastic deformation of the tubular member has been described that includes an expansion surface coupled to the expansion device defining a surface texture, wherein the  $R_a$  for the expansion surface is less than or equal to 60.205 nm.

**[00125]** A tribological system for lubricating an interface between an expansion device and a tubular member during a radial expansion and plastic deformation of the tubular member has been described that includes an expansion surface coupled to the expansion device defining a surface texture, wherein the  $R_z$  for the expansion surface is less than or equal to 1.99 nm.

**[00126]** A tribological system for lubricating an interface between an expansion device and a tubular member during a radial expansion and plastic deformation of the tubular member has been described that includes an expansion surface coupled to the expansion device defining a surface texture, wherein the  $R_a$  for the expansion surface is about 60.205 nm.

**[00127]** A tribological system for lubricating an interface between an expansion device and a tubular member during a radial expansion and plastic deformation of the tubular member has been described that includes an expansion surface coupled to the expansion device defining a surface texture, wherein the  $R_z$  for the expansion surface is about 1.99 nm.

**[00128]** A tribological system for lubricating an interface between an expansion device and a tubular member during a radial expansion and plastic deformation of the tubular member has been described that includes an expansion surface coupled to the expansion device defining a surface texture, wherein the  $R_a$  for the expansion surface is less than or equal to 277.930 nm.

**[00129]** A tribological system for lubricating an interface between an expansion device and a tubular member during a radial expansion and plastic deformation of the tubular member has been described that includes an expansion surface coupled to the expansion device defining a surface texture, wherein the  $R_z$  for the expansion surface is less than or equal to 3.13 nm.

**[00130]** A tribological system for lubricating an interface between an expansion device and a tubular member during a radial expansion and plastic deformation of the tubular member has been described that includes an expansion surface coupled to the expansion device defining a surface texture, wherein the  $R_a$  for the expansion surface is less than or equal to 277.930 nm and greater than or equal to 60.205 nm.

**[00131]** A tribological system for lubricating an interface between an expansion device and a tubular member during a radial expansion and plastic deformation of the tubular member has been described that includes an expansion surface coupled

to the expansion device defining a surface texture, wherein the  $R_z$  for the expansion surface is less than or equal to 3.13 nm and greater than or equal to 1.99 nm.

**[00132]** A tribological system for lubricating an interface between an expansion device and a tubular member during a radial expansion and plastic deformation of the tubular member has been described that includes an expansion surface coupled to the expansion device defining a surface texture, wherein the expansion surface comprises a plateau-like surface that defines one or more relatively deep recesses.

**[00133]** A tribological system for lubricating an interface between an expansion device and a tubular member during a radial expansion and plastic deformation of the tubular member has been described that includes an expansion surface coupled to the expansion device defining a surface texture, and a lubricating film coupled to the expansion surface, wherein the first lubricating film includes chromium nitride.

**[00134]** A tribological system for lubricating an interface between an expansion device and a tubular member during a radial expansion and plastic deformation of the tubular member has been described that includes an expansion surface coupled to the expansion device defining a surface texture, and a lubricating film coupled to an interior surface of the tubular member, wherein the lubricating film includes PTFE.

**[00135]** A tribological system for lubricating an interface between an expansion device and a tubular member during a radial expansion and plastic deformation of the tubular member has been described that includes an expansion surface coupled to the expansion device defining a surface texture, wherein the expansion surface comprises DC53 tool steel.

**[00136]** A tribological system for lubricating an interface between an expansion device and a tubular member during a radial expansion and plastic deformation of the tubular member has been described that includes an expansion surface coupled to the expansion, wherein the coefficient of friction for the interface is less than or equal to 0.125.

**[00137]** A tribological system for lubricating an interface between an expansion device and a tubular member during a radial expansion and plastic deformation of the tubular member has been described that includes an expansion surface coupled to the expansion, wherein the coefficient of friction for the interface is less than 0.125.

**[00138]** A tribological system for lubricating an interface between an expansion device and a tubular member during a radial expansion and plastic deformation of

the tubular member has been described that includes an expansion surface coupled to the expansion, wherein the coefficient of friction for the interface is less than or equal to 0.06.

**[00139]** A tribological system for lubricating an interface between an expansion device and a tubular member during a radial expansion and plastic deformation of the tubular member has been described that includes an expansion surface coupled to the expansion, wherein the coefficient of friction for the interface is less than 0.06.

**[00140]** A tribological system for lubricating an interface between an expansion device and a tubular member during a radial expansion and plastic deformation of the tubular member has been described that includes an expansion surface coupled to the expansion, wherein the expansion surface comprises a polished surface.

**[00141]** A tribological system for lubricating an interface between an expansion device and a tubular member during a radial expansion and plastic deformation of the tubular member has been described that includes an expansion surface coupled to the expansion, wherein the forces required to overcome friction during the radial expansion and plastic deformation of the tubular member are less than or equal to 45% of the total forces required to radially expand and plastically deform the tubular member.

**[00142]** A tribological system for lubricating an interface between an expansion device and a tubular member during a radial expansion and plastic deformation of the tubular member has been described that includes an expansion surface coupled to the expansion, wherein the forces required to overcome friction during the radial expansion and plastic deformation of the tubular member are less than 45% of the total forces required to radially expand and plastically deform the tubular member.

**[00143]** A tribological system for lubricating an interface between an expansion device and a tubular member during a radial expansion and plastic deformation of the tubular member has been described that includes an expansion surface coupled to the expansion, wherein the forces required to overcome friction during the radial expansion and plastic deformation of the tubular member are less than or equal to 8% of the total forces required to radially expand and plastically deform the tubular member.

**[00144]** A tribological system for lubricating an interface between an expansion device and a tubular member during a radial expansion and plastic deformation of the tubular member has been described that includes an expansion surface coupled

to the expansion, wherein the forces required to overcome friction during the radial expansion and plastic deformation of the tubular member are less than 8% of the total forces required to radially expand and plastically deform the tubular member.

**[00145]** A tribological system for lubricating an interface between an expansion device and a tubular member during a radial expansion and plastic deformation of the tubular member has been described that includes an expansion surface coupled to the expansion, wherein the bearing ratio of the expansion surface varies less than about 15%.

**[00146]** A tribological system for lubricating an interface between an expansion device and a tubular member during a radial expansion and plastic deformation of the tubular member has been described that includes an expansion surface coupled to the expansion, wherein the bearing ratio of the expansion surface of the expansion device is greater than 75% on 60% of the  $R_z$  surface roughness.

**[00147]** It is understood that variations may be made in the foregoing without departing from the scope of the invention. For example, the teachings of the present illustrative embodiments may be used to provide a wellbore casing, a pipeline, or a structural support. Furthermore, the elements and teachings of the various illustrative embodiments may be combined in whole or in part in some or all of the illustrative embodiments.

**[00148]** Although illustrative embodiments of the invention have been shown and described, a wide range of modification, changes and substitution is contemplated in the foregoing disclosure. In some instances, some features of the present invention may be employed without a corresponding use of the other features. Accordingly, it is appropriate that the appended claims be construed broadly and in a manner consistent with the scope of the invention.

### Claims

What is claimed is:

1. An expansion cone for radially expanding multiple tubular members comprising:
  - a body having an annular outer peripheral surface;
  - at least a portion of the surface being textured with friction reducing reliefs recessed into the surface.
2. The expansion cone as defined in claim 1 wherein the surface is a knurled surface.
3. The expansion cone as defined in claim 1 wherein the surface is a laser dimpled surface.
4. The expansion cone as defined in claim 1 wherein the surface is a pitted and sprayed surface.
5. The expansion cone as defined in claim 4 wherein the body includes the pitted surface formed of a first material, the pitted surface being sprayed with a second friction reducing material and the sprayed surface being partially removed sufficient to expose some of the first and second materials.
6. The expansion cone as defined in claim 1 wherein the surface is an etched surface.
7. A method for radially expanding a tubular member comprising:
  - providing a tubular member having an inside diameter;
  - providing an expansion cone having an annular outer peripheral surface including a diameter greater than the inside diameter of the tubular member;
  - texturing the outer peripheral surface with friction reducing reliefs recessed into the surface; and
  - moving the expansion cone axially through the tubular member for radially expanding and plastically deforming the tubular member.
8. The method as defined in claim 7 wherein the surface is a knurled surface.
9. The method as defined in claim 7 wherein the surface is a laser dimpled surface.
10. The method as defined in claim 7 wherein the surface is a pitted and sprayed surface.



11. The method as defined in claim 7 further comprising:
  - pitting the outer peripheral surface;
  - spraying the surface; and
  - grinding the surface to expose both an original portion of the surface and a sprayed portion of the surface.
12. The method as defined in claim 7 wherein the surface is an etched surface.
13. A reduced friction radial expansion apparatus comprising:
  - a plurality of tubular members having an axial passage formed therethrough including an inside diameter;
  - an expansion cone having an annular outer peripheral surface including an outside diameter greater than the inside diameter of the axial passage; and
  - at least a portion of the outer peripheral surface being textured with friction reducing reliefs recessed into the surface.
14. The apparatus as defined in claim 13 wherein the surface is a knurled surface.
15. The apparatus as defined in claim 13 wherein the surface is a laser dimpled surface.
16. The apparatus as defined in claim 13 wherein the surface is a pitted and sprayed surface.
17. The apparatus as defined in claim 13 wherein the cone includes a pitted surface formed of a first material, the pitted surface being sprayed with a second friction reducing material and the sprayed surface being partially removed sufficient to expose some of the first and second materials.
18. The apparatus as defined in claim 13 wherein the surface is an etched surface.
19. The apparatus as defined in claim 13 wherein a low friction material is deposited in the reliefs.
20. The apparatus as defined in claim 13 wherein the outer peripheral surface includes a flush surface including a combination of portions of material of the expansion cone and portions of a low friction material deposited in the reliefs.
21. An apparatus for radially expanding and plastically deforming a tubular member, comprising:
  - a support member;

- an expansion device coupled to an end of the support member comprising one or more expansion surfaces for engaging the tubular member during the radial expansion and plastic deformation of the tubular member; and
- a lubrication system for lubricating an interface between one or more of the expansion surfaces of the expansion device and one or more interior surfaces of the tubular member.
22. The apparatus of claim 21, wherein the lubrication system comprises:  
a supply of a lubricant; and  
an injector for injecting the lubricant into the interface.
23. The apparatus of claim 22, wherein the supply of lubricant is provided within the expansion device.
24. The apparatus of claim 21, wherein one or more of the expansion surfaces define one or more recesses; and wherein one or more of the recesses are coupled to the injector.
25. The apparatus of claim 21, wherein the lubrication system comprises:  
a lubricating film coupled to one or more of the expansion surfaces.
26. The apparatus of claim 25, wherein one or more of the expansion surfaces define one or more recesses; and wherein at least a portion of the lubricating film is deposited within one or more of the recesses.
27. The apparatus of claim 21, wherein one or more of the expansion surfaces of the expansion device define one or more recesses.
28. The apparatus of claim 27, wherein at least some of the recesses are identical to one another.
29. The apparatus of claim 27, wherein at least some of the recesses are equally spaced from one another.
30. The apparatus of claim 27, wherein a depth dimension of the recesses are non-uniform.
31. The apparatus of claim 27, wherein at least some of the recesses intersect.
32. The apparatus of claim 27, wherein the location of at least some of the recesses is randomly distributed.
33. The apparatus of claim 27, wherein the geometry of at least some of the recesses is randomly distributed.

34. The apparatus of claim 27, wherein a surface texture of at least some of the recesses is randomly distributed.
35. The apparatus of claim 27, wherein the geometry of at least some of the recesses is linear.
36. The apparatus of claim 27, wherein the geometry of at least some of the recesses is non-linear.
37. The apparatus of claim 27, wherein the interface comprises a leading edge portion and a trailing edge portion; and wherein the lubrication system provides a higher lubrication concentration in at least one of the leading and trailing edge portions.
38. The apparatus of claim 21, wherein one or more of the expansion surfaces of the expansion device define one or more recesses; and wherein the apparatus further comprises one or more lubricating ball bearings supported within at least one of the recesses.
39. The apparatus of claim 21, wherein a lubrication concentration provided by the lubrication system is varied as a function of a rate of strain of the tubular member during an operation of the apparatus.
40. The apparatus of claim 39, wherein the function comprises a linear function.
41. The apparatus of claim 39, wherein the function comprises a non-linear function.
42. The apparatus of claim 39, wherein the function comprises a step function.
43. A method for radially expanding and plastically deforming a tubular member, comprising:  
radially expanding and plastically deforming the tubular member using an expansion device comprising one or more expansion surfaces; and lubricating an interface between one or more of the expansion surfaces of the expansion device and one or more interior surfaces of the tubular member.
44. The method of claim 43, further comprising:  
injecting a supply of lubricant into the interface.
45. The method of claim 44, wherein the supply of lubricant is provided within the expansion device.

46. The method of claim 43, wherein one or more of the expansion surfaces define one or more recesses; and wherein the method further comprises injecting the supply of lubricant into one or more of the recesses.
47. The method of claim 43, further comprising:  
coupling a lubricating film to one or more of the expansion surfaces.
48. The method of claim 47, wherein one or more of the expansion surfaces define one or more recesses; and wherein at least a portion of the lubricating film is coupled to one or more of the recesses.
49. The method of claim 43, wherein one or more of the expansion surfaces of the expansion device define one or more recesses.
50. The method of claim 49, wherein at least some of the recesses are identical to one another.
51. The method of claim 49, wherein at least some of the recesses are equally spaced from one another.
52. The method of claim 49, wherein a depth dimension of the recesses are non-uniform.
53. The method of claim 49, wherein at least some of the recesses intersect.
54. The method of claim 49, wherein the location of at least some of the recesses is randomly distributed.
55. The method of claim 49, wherein the geometry of at least some of the recesses is randomly distributed.
56. The method of claim 49, wherein a surface texture of at least some of the recesses is randomly distributed.
57. The method of claim 49, wherein the geometry of at least some of the recesses is linear.
58. The method of claim 49, wherein the geometry of at least some of the recesses is non-linear.
59. The method of claim 49, wherein the interface comprises a leading edge portion and a trailing edge portion; and wherein the method further comprises providing a higher lubrication concentration in at least one of the leading and trailing edge portions.
60. The method of claim 43, wherein one or more of the expansion surfaces of the expansion device define one or more recesses; and wherein the method

further comprises forming one or more lubricating ball bearings within at least one of the recesses.

61. The method of claim 43, further comprising varying a lubrication concentration as a function of a rate of strain of the tubular member during the radial expansion and plastic deformation of the tubular member.
62. The method of claim 61, wherein the function comprises a linear function.
63. The method of claim 61, wherein the function comprises a non-linear function.
64. The method of claim 61, wherein the function comprises a step function.
65. A system for lubricating an interface between an expansion device and a tubular member during a radial expansion of the tubular member by the expansion device, comprising:  
means for supplying a quantity of a lubricant material; and  
means for injecting at least a portion of the lubricant material into the interface.
66. The system of claim 65, further comprising:  
means for varying the concentration of the lubricant material within the interface.
67. A method of operating a system for lubricating an interface between an expansion device and a tubular member during a radial expansion of the tubular member by the expansion device, comprising:  
determining a rate of strain of the tubular member during an operation of the expansion device; and  
varying a concentration of a lubricant material within the interface during the operation of the expansion device as a function of the determined rate of strain.
68. A method of operating a system for lubricating an interface between an expansion device and a tubular member during a radial expansion of the tubular member by the expansion device, comprising:  
determining one or more characteristics of the interface during an operation of the expansion device; and  
varying a concentration of a lubricant material within the interface during the operation of the expansion device as a function of one or more of the determined characteristics.

69. A system for lubricating an interface between an expansion device and a tubular member during a radial expansion of the tubular member by the expansion device, comprising:  
means for determining a rate of strain of the tubular member during an operation of the expansion device; and  
means for varying a concentration of a lubricant material within the interface during the operation of the expansion device as a function of the determined rate of strain.
70. A system for lubricating an interface between an expansion device and a tubular member during a radial expansion of the tubular member by the expansion device, comprising:  
means for determining one or more characteristics of the interface during an operation of the expansion device; and  
means for varying a concentration of a lubricant material within the interface during the operation of the expansion device as a function of one or more of the determined characteristics.
71. A method of operating a system for lubricating an interface between an expansion device and a tubular member during a radial expansion of the tubular member by the expansion device, comprising:  
determining one or more characteristics of the operation of the expansion device; and  
varying a concentration of a lubricant material within the interface during the operation of the expansion device as a function of one or more of the determined characteristics.
72. A system for lubricating an interface between an expansion device and a tubular member during a radial expansion of the tubular member by the expansion device, comprising:  
means for determining one or more characteristics of the operation of the expansion device; and  
means for varying a concentration of a lubricant material within the interface during the operation of the expansion device as a function of one or more of the determined characteristics.
73. An apparatus for radially expanding and plastically deforming a tubular member, comprising:

- a support member;
  - an expansion device coupled to an end of the support member comprising
    - one or more expansion surfaces for engaging the tubular member during the radial expansion and plastic deformation of the tubular member, wherein at least a portion of at least one of the expansion surfaces define one or more recesses; and
  - a lubrication system for lubricating an interface between one or more of the expansion surfaces of the expansion device and one or more interior surfaces of the tubular member comprising:
    - a lubricating film coupled to at least one of the recesses of the expansion surfaces of the expansion device;
    - a supply of lubricant; and
    - an injector coupled to the supply of lubricant and at least one of the recesses of the expansion surfaces for injecting the supply of lubricant into at least one of the recesses.
74. A method for radially expanding and plastically deforming a tubular member, comprising:
- radially expanding and plastically deforming the tubular member using an expansion device comprising one or more expansion surfaces, wherein one or more of the expansion surfaces define one or more recesses; and
  - lubricating an interface between one or more of the expansion surfaces of the expansion device and one or more interior surfaces of the tubular member by:
    - coating at least one of the recesses with a lubricating film; and
    - injecting a lubricant material into at least one of the recesses.
75. A tribological system for lubricating an interface between an expansion device and a tubular member during a radial expansion and plastic deformation of the tubular member, comprising:
- an expansion surface coupled to the expansion device defining a surface texture;
  - a first lubricating film coupled to the expansion surface;
  - a second lubricating film coupled to an interior surface of the tubular member;
  - and

a lubricating material disposed within an annulus defined between the expansion surface of the expansion device and the interior surface of the tubular member.

76. The system of claim 75, wherein a resistance to abrasion of the first lubricating film is greater than a resistance to abrasion of the second lubricating film.
77. The system of claim 75, wherein the  $R_a$  for the expansion surface is less than or equal to 60.205 nm.
78. The system of claim 75, wherein the  $R_z$  for the expansion surface is less than or equal to 1.99 nm.
79. The system of claim 75, wherein the  $R_a$  for the expansion surface is about 60.205 nm.
80. The system of claim 75, wherein the  $R_z$  for the expansion surface is about 1.99 nm.
81. The system of claim 75, wherein the  $R_a$  for the expansion surface is less than or equal to 277.930 nm.
82. The system of claim 75, wherein the  $R_z$  for the expansion surface is less than or equal to 3.13 nm.
83. The system of claim 75, wherein the  $R_a$  for the expansion surface is less than or equal to 277.930 nm and greater than or equal to 60.205 nm.
84. The system of claim 75, wherein the  $R_z$  for the expansion surface is less than or equal to 3.13 nm and greater than or equal to 1.99 nm.
85. The system of claim 75, wherein the expansion surface comprises a plateau-like surface that defines one or more relatively deep recesses.
86. The system of claim 75, wherein the first lubricating film comprises chromium nitride.
87. The system of claim 75, wherein the second lubricating film comprises PTFE.
88. The system of claim 75, wherein the expansion surface comprises DC53 tool steel.
89. The system of claim 75, wherein the coefficient of friction for the interface is less than or equal to 0.125.
90. The system of claim 75, wherein the coefficient of friction for the interface is less than 0.125.
91. The system of claim 75, wherein the coefficient of friction for the interface is less than or equal to 0.125 and greater than or equal to 0.06.



92. The system of claim 75, wherein the coefficient of friction for the interface is less than or equal to 0.06.
93. The system of claim 75, wherein the expansion surface comprises a polished surface.
94. The system of claim 75, wherein the forces required to overcome friction during the radial expansion and plastic deformation of the tubular member are less than or equal to 45% of the total forces required to radially expand and plastically deform the tubular member.
95. The system of claim 75, wherein the forces required to overcome friction during the radial expansion and plastic deformation of the tubular member are less than 45% of the total forces required to radially expand and plastically deform the tubular member.
96. The system of claim 75, wherein the forces required to overcome friction during the radial expansion and plastic deformation of the tubular member are less than or equal to 45% and greater than or equal to 8% of the total forces required to radially expand and plastically deform the tubular member.
97. The system of claim 75, wherein the forces required to overcome friction during the radial expansion and plastic deformation of the tubular member are less than or equal to 8% of the total forces required to radially expand and plastically deform the tubular member.
98. The system of claim 75, wherein the bearing ratio of the expansion surface varies less than about 15%.
99. The system of claim 75, wherein the bearing ratio of the expansion surface of the expansion device is greater than 75% on 60% of the  $R_z$  surface roughness.
100. A method of lubricating an interface between an expansion surface of an expansion device and a tubular member during a radial expansion and plastic deformation of the tubular member, comprising:  
texturing the expansion surface;  
coupling a first lubricating film coupled to the expansion surface;  
coupling a second lubricating film to an interior surface of the tubular member;  
and  
disposing a lubricating material within an annulus defined between the expansion surface of the expansion device and the interior surface of the tubular member.

101. The method of claim 100, wherein a resistance to abrasion of the first lubricating film is greater than a resistance to abrasion of the second lubricating film.
102. The method of claim 100, wherein the  $R_a$  for the expansion surface is less than or equal to 60.205 nm.
103. The method of claim 100, wherein the  $R_z$  for the expansion surface is less than or equal to 1.99 nm.
104. The method of claim 100, wherein the  $R_a$  for the expansion surface is about 60.205 nm.
105. The method of claim 100, wherein the  $R_z$  for the expansion surface is about 1.99 nm.
106. The method of claim 100, wherein the  $R_a$  for the expansion surface is less than or equal to 277.930 nm.
107. The method of claim 100, wherein the  $R_z$  for the expansion surface is less than or equal to 3.13 nm.
108. The method of claim 100, wherein the  $R_a$  for the expansion surface is less than or equal to 277.930 nm and greater than or equal to 60.205 nm.
109. The method of claim 100, wherein the  $R_z$  for the expansion surface is less than or equal to 3.13 nm and greater than or equal to 1.99 nm.
110. The method of claim 100, wherein the expansion surface comprises a plateau-like surface that defines one or more relatively deep recesses.
111. The method of claim 100, wherein the first lubricating film comprises chromium nitride.
112. The method of claim 100, wherein the second lubricating film comprises PTFE.
113. The method of claim 100, wherein the expansion surface comprises DC53 tool steel.
114. The method of claim 100, wherein the coefficient of friction for the interface is less than or equal to 0.125.
115. The method of claim 100, wherein the coefficient of friction for the interface is less than or equal to 0.125 and greater than or equal to 0.06.
116. The method of claim 100, wherein the coefficient of friction for the interface is less than 0.125 and greater than or equal to 0.06.
117. The method of claim 100, wherein the coefficient of friction for the interface is less or equal to 0.06.

118. The method of claim 100, further comprising polishing the expansion surface.

119. The method of claim 100, wherein the forces required to overcome friction during the radial expansion and plastic deformation of the tubular member are less than or equal to 45% of the total forces required to radially expand and plastically deform the tubular member.

120. The method of claim 100, wherein the forces required to overcome friction during the radial expansion and plastic deformation of the tubular member are less than 45% of the total forces required to radially expand and plastically deform the tubular member.

121. The method of claim 100, wherein the forces required to overcome friction during the radial expansion and plastic deformation of the tubular member are less than or equal to 45% and greater than or equal to 8% of the total forces required to radially expand and plastically deform the tubular member.

122. The method of claim 100, wherein the forces required to overcome friction during the radial expansion and plastic deformation of the tubular member are less than or equal to 8% of the total forces required to radially expand and plastically deform the tubular member.

123. The method of claim 100, wherein the bearing ratio of the expansion surface varies less than about 15%.

124. The method of claim 100, wherein the bearing ratio of the expansion surface of the expansion device is greater than 75% on 60% of the  $R_z$  surface roughness.

125. A system for radially expanding and plastically deforming a tubular member, wherein the amount of energy required to overcome frictional forces during the radial expansion and plastic deformation of the tubular member is less than or equal to 45% of the total amount of energy required to radially expand and plastically deform the tubular member.

126. A system for radially expanding and plastically deforming a tubular member comprising an expansion device, wherein the coefficient of friction between the expansion device and the tubular member during the radial expansion and plastic deformation of the tubular member is less than or equal to 0.125.

127. A system for radially expanding and plastically deforming a tubular member, wherein the amount of energy required to overcome frictional forces during the radial expansion and plastic deformation of the tubular member is less than or equal to

45% and greater than or equal to 8% of the total amount of energy required to radially expand and plastically deform the tubular member.

128. A system for radially expanding and plastically deforming a tubular member comprising an expansion device, wherein the coefficient of friction between the expansion device and the tubular member during the radial expansion and plastic deformation of the tubular member is less than or equal to 0.06.

129. A tribological system for lubricating an interface between an expansion device and a tubular member during a radial expansion and plastic deformation of the tubular member, comprising:

an expansion surface coupled to the expansion device defining a surface texture;

a first lubricating film coupled to the expansion surface; and

a second lubricating film coupled to an interior surface of the tubular member;

wherein a resistance to abrasion of the first lubricating film is greater than a resistance to abrasion of the second lubricating film.

130. A tribological system for lubricating an interface between an expansion device and a tubular member during a radial expansion and plastic deformation of the tubular member, comprising:

an expansion surface coupled to the expansion device defining a surface texture;

wherein the  $R_a$  for the expansion surface is less than or equal to 60.205 nm.

131. A tribological system for lubricating an interface between an expansion device and a tubular member during a radial expansion and plastic deformation of the tubular member, comprising:

an expansion surface coupled to the expansion device defining a surface texture;

wherein the  $R_z$  for the expansion surface is less than or equal to 1.99 nm.

132. A tribological system for lubricating an interface between an expansion device and a tubular member during a radial expansion and plastic deformation of the tubular member, comprising:

an expansion surface coupled to the expansion device defining a surface texture;

wherein the  $R_a$  for the expansion surface is about 60.205 nm.

133. A tribological system for lubricating an interface between an expansion device and a tubular member during a radial expansion and plastic deformation of the tubular member, comprising:

an expansion surface coupled to the expansion device defining a surface texture;

wherein the  $R_z$  for the expansion surface is about 1.99 nm.

134. A tribological system for lubricating an interface between an expansion device and a tubular member during a radial expansion and plastic deformation of the tubular member, comprising:

an expansion surface coupled to the expansion device defining a surface texture;

wherein the  $R_a$  for the expansion surface is less than or equal to 277.930 nm.

135. A tribological system for lubricating an interface between an expansion device and a tubular member during a radial expansion and plastic deformation of the tubular member, comprising:

an expansion surface coupled to the expansion device defining a surface texture;

wherein the  $R_z$  for the expansion surface is less than or equal to 3.13 nm.

136. A tribological system for lubricating an interface between an expansion device and a tubular member during a radial expansion and plastic deformation of the tubular member, comprising:

an expansion surface coupled to the expansion device defining a surface texture;

wherein the  $R_a$  for the expansion surface is less than or equal to 277.930 nm and greater than or equal to 60.205 nm.

137. A tribological system for lubricating an interface between an expansion device and a tubular member during a radial expansion and plastic deformation of the tubular member, comprising:

an expansion surface coupled to the expansion device defining a surface texture;

wherein the  $R_z$  for the expansion surface is less than or equal to 3.13 nm and greater than or equal to 1.99 nm.

138. A tribological system for lubricating an interface between an expansion device and a tubular member during a radial expansion and plastic deformation of the tubular member, comprising:

an expansion surface coupled to the expansion device defining a surface texture;

wherein the expansion surface comprises a plateau-like surface that defines one or more relatively deep recesses.

139. A tribological system for lubricating an interface between an expansion device and a tubular member during a radial expansion and plastic deformation of the tubular member, comprising:

an expansion surface coupled to the expansion device defining a surface texture; and

a lubricating film coupled to the expansion surface;

wherein the first lubricating film comprises chromium nitride.

140. A tribological system for lubricating an interface between an expansion device and a tubular member during a radial expansion and plastic deformation of the tubular member, comprising:

an expansion surface coupled to the expansion device defining a surface texture; and

a lubricating film coupled to an interior surface of the tubular member;

wherein the lubricating film comprises PTFE.

141. A tribological system for lubricating an interface between an expansion device and a tubular member during a radial expansion and plastic deformation of the tubular member, comprising:

an expansion surface coupled to the expansion device defining a surface texture;

wherein the expansion surface comprises DC53 tool steel.

142. A tribological system for lubricating an interface between an expansion device and a tubular member during a radial expansion and plastic deformation of the tubular member, comprising:

an expansion surface coupled to the expansion device;

wherein the coefficient of friction for the interface is less than or equal to 0.125.

143. A tribological system for lubricating an interface between an expansion device and a tubular member during a radial expansion and plastic deformation of the tubular member, comprising:

- an expansion surface coupled to the expansion device;
- wherein the coefficient of friction for the interface is less than 0.125.

144. A tribological system for lubricating an interface between an expansion device and a tubular member during a radial expansion and plastic deformation of the tubular member, comprising:

- an expansion surface coupled to the expansion device;
- wherein the coefficient of friction for the interface is less than or equal to 0.125 and greater than or equal to 0.06.

145. A tribological system for lubricating an interface between an expansion device and a tubular member during a radial expansion and plastic deformation of the tubular member, comprising:

- an expansion surface coupled to the expansion device;
- wherein the coefficient of friction for the interface is less than or equal to 0.06.

146. A tribological system for lubricating an interface between an expansion device and a tubular member during a radial expansion and plastic deformation of the tubular member, comprising:

- an expansion surface coupled to the expansion device;
- wherein the expansion surface comprises a polished surface.

147. A tribological system for lubricating an interface between an expansion device and a tubular member during a radial expansion and plastic deformation of the tubular member, comprising:

- an expansion surface coupled to the expansion device;
- wherein the forces required to overcome friction during the radial expansion and plastic deformation of the tubular member are less than or equal to 45% of the total forces required to radially expand and plastically deform the tubular member.

148. A tribological system for lubricating an interface between an expansion device and a tubular member during a radial expansion and plastic deformation of the tubular member, comprising:

- an expansion surface coupled to the expansion device;

wherein the forces required to overcome friction during the radial expansion and plastic deformation of the tubular member are less than 45% of the total forces required to radially expand and plastically deform the tubular member.

149. A tribological system for lubricating an interface between an expansion device and a tubular member during a radial expansion and plastic deformation of the tubular member, comprising:

an expansion surface coupled to the expansion device;

wherein the forces required to overcome friction during the radial expansion and plastic deformation of the tubular member are less than or equal to 45% and greater than or equal to 8% of the total forces required to radially expand and plastically deform the tubular member.

150. A tribological system for lubricating an interface between an expansion device and a tubular member during a radial expansion and plastic deformation of the tubular member, comprising:

an expansion surface coupled to the expansion device;

wherein the forces required to overcome friction during the radial expansion and plastic deformation of the tubular member are less than or equal to 8% of the total forces required to radially expand and plastically deform the tubular member.

151. A tribological system for lubricating an interface between an expansion device and a tubular member during a radial expansion and plastic deformation of the tubular member, comprising:

an expansion surface coupled to the expansion device;

wherein the bearing ratio of the expansion surface varies less than about 15%.

152. A tribological system for lubricating an interface between an expansion device and a tubular member during a radial expansion and plastic deformation of the tubular member, comprising:

an expansion surface coupled to the expansion device;

wherein the bearing ratio of the expansion surface of the expansion device is greater than 75% on 60% of the  $R_z$  surface roughness.



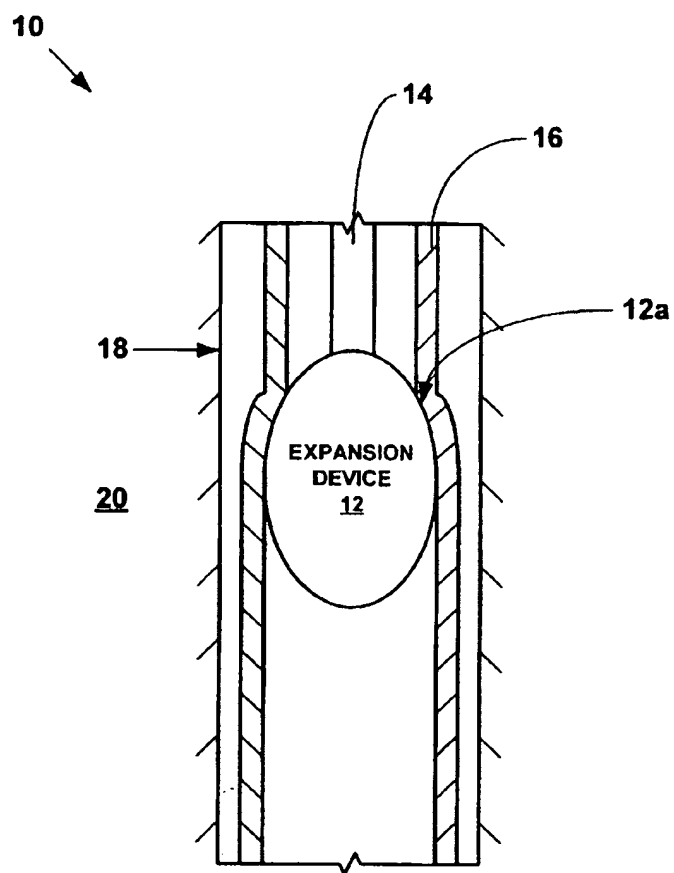


Fig. 1a

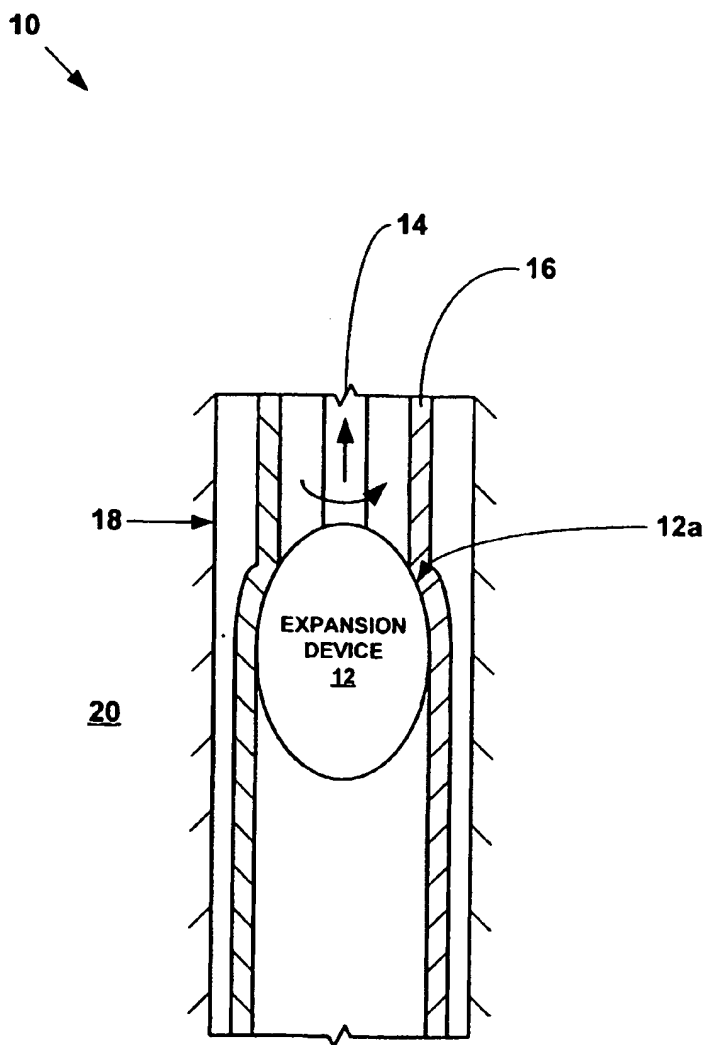


Fig. 1b

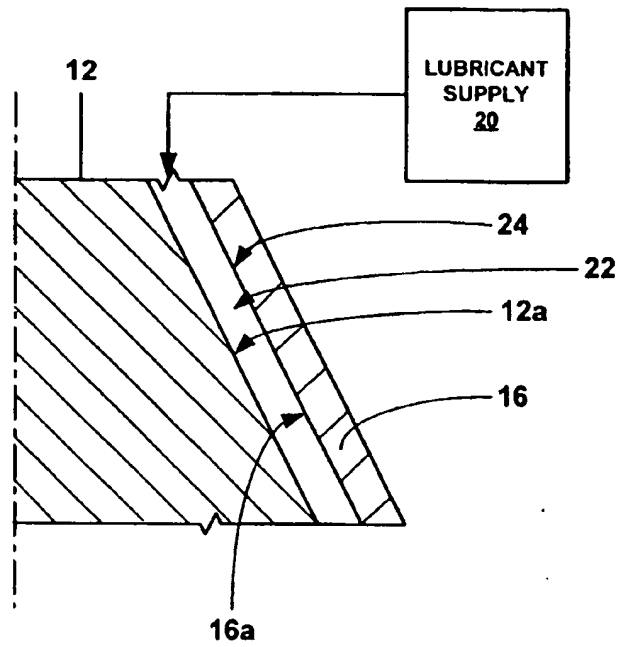


Fig. 2

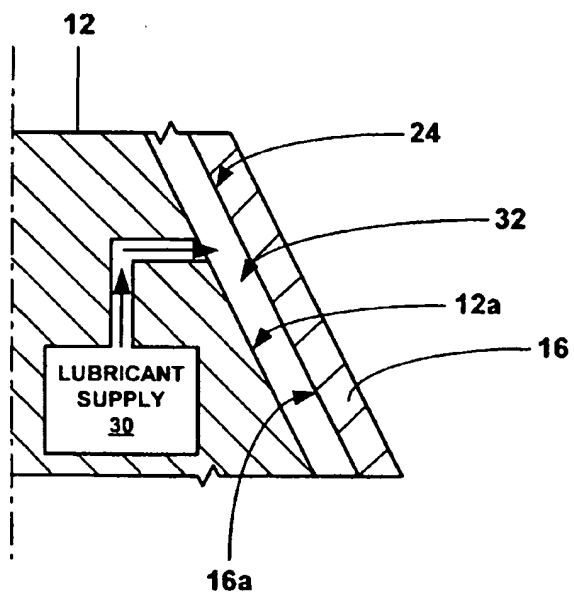


Fig. 3

Fig. 4

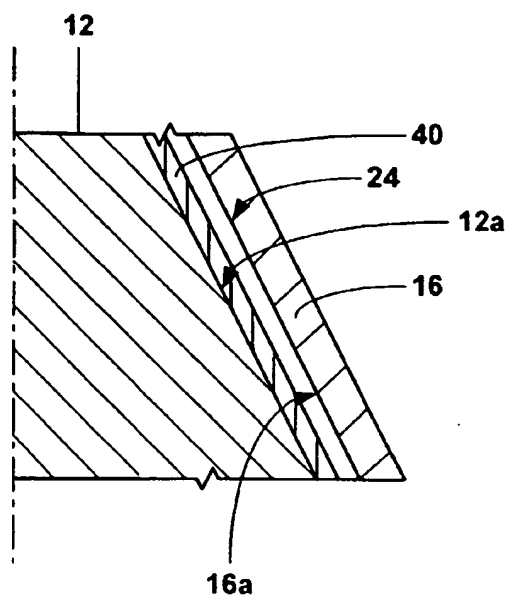
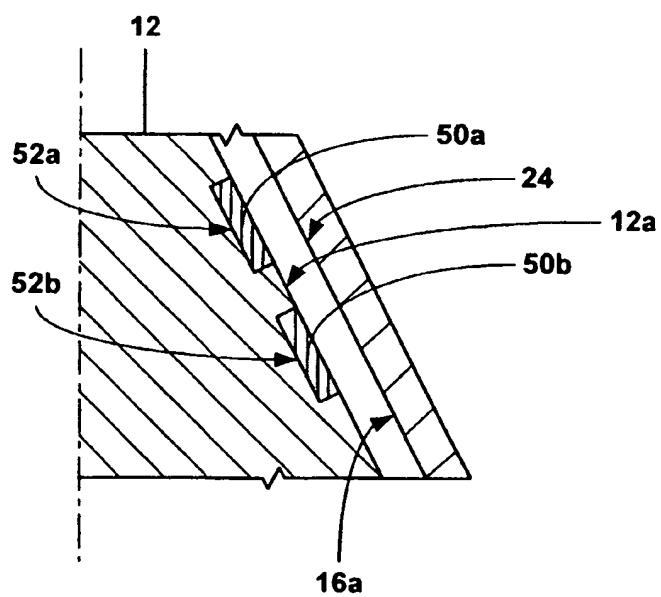


Fig. 5



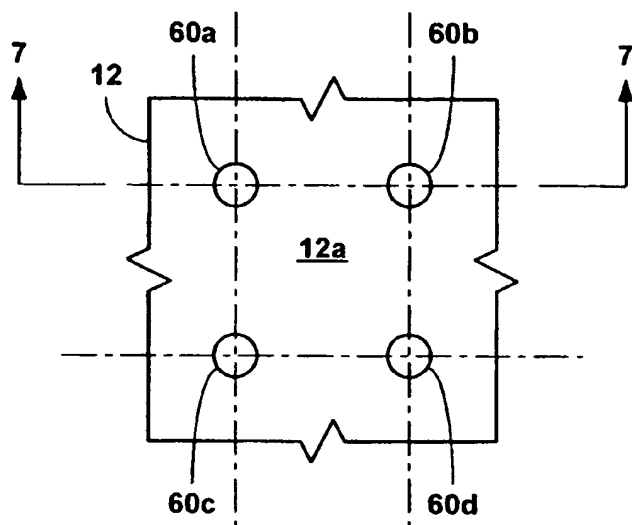


Fig. 6

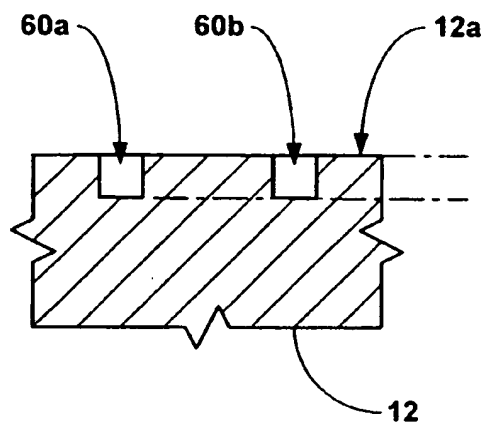


Fig. 7

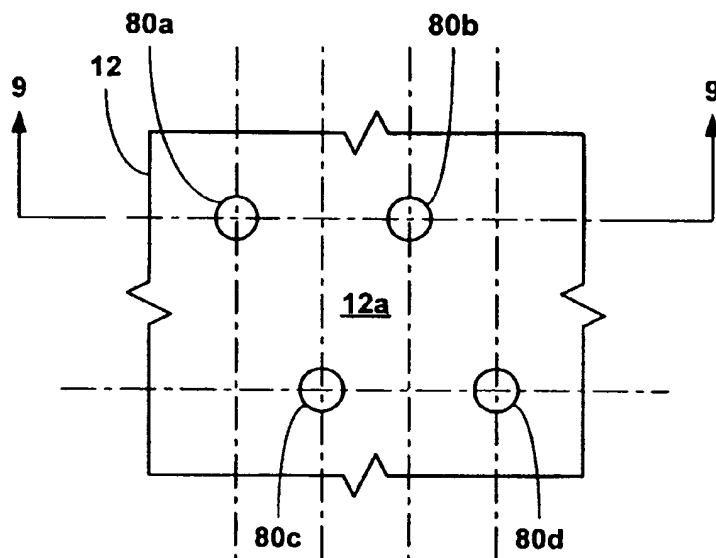


Fig. 8

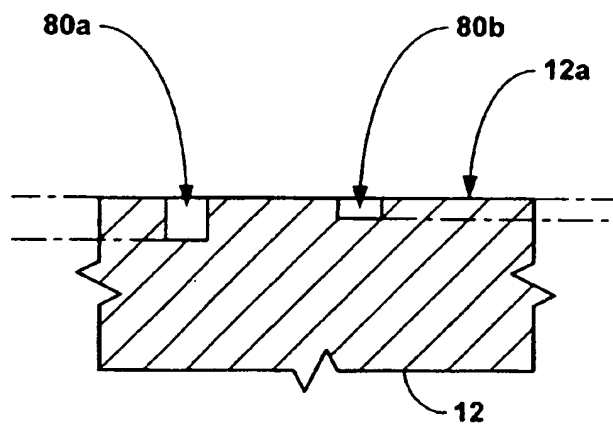


Fig. 9

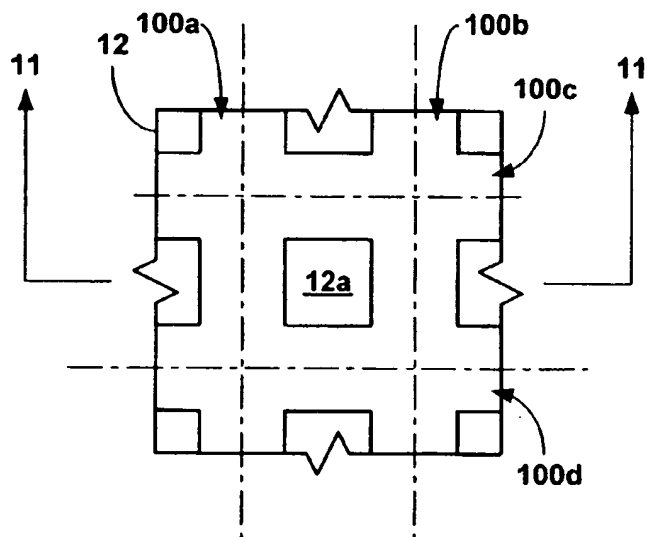


Fig. 10

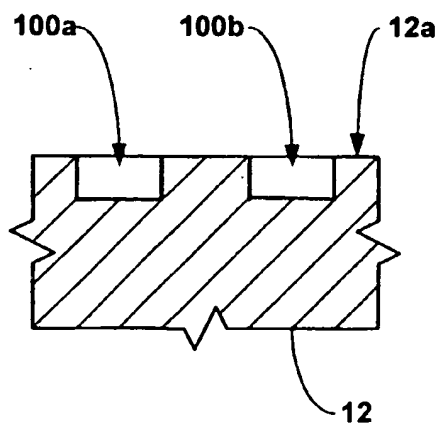


Fig. 11

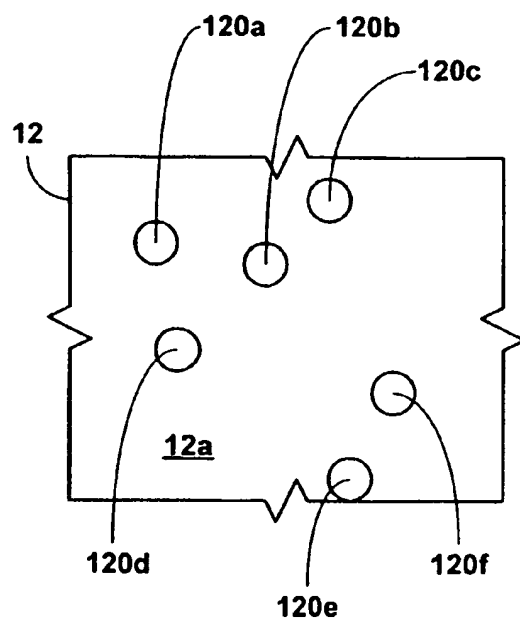


Fig. 12

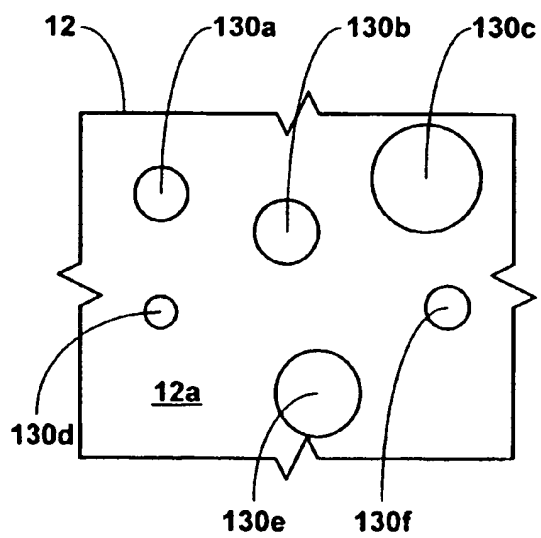


Fig. 13



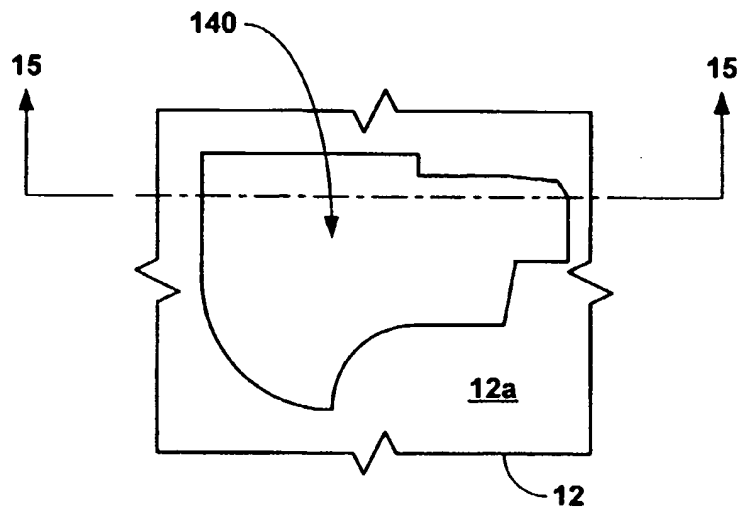


Fig. 14

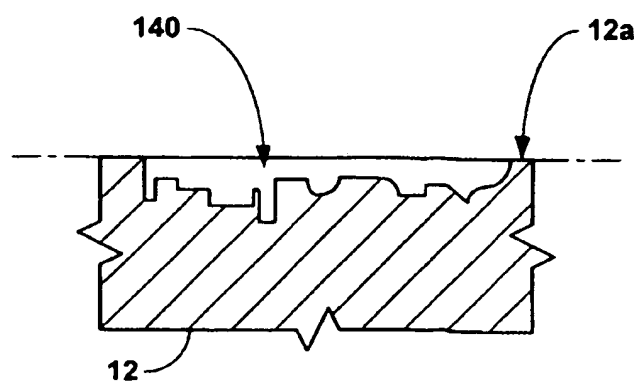


Fig. 15

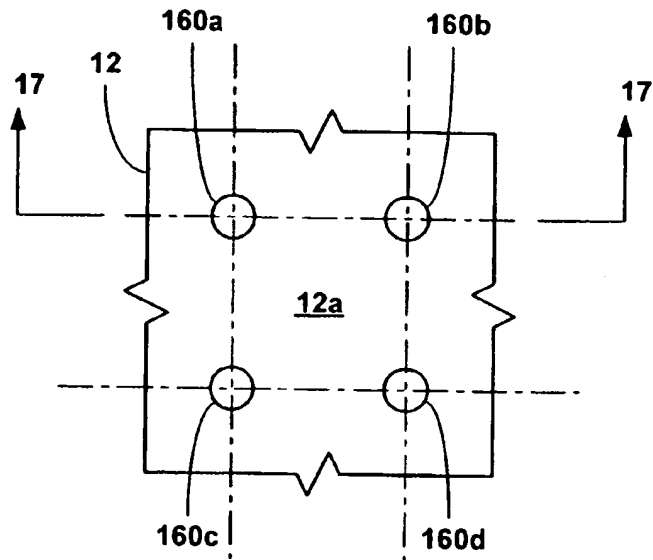


Fig. 16

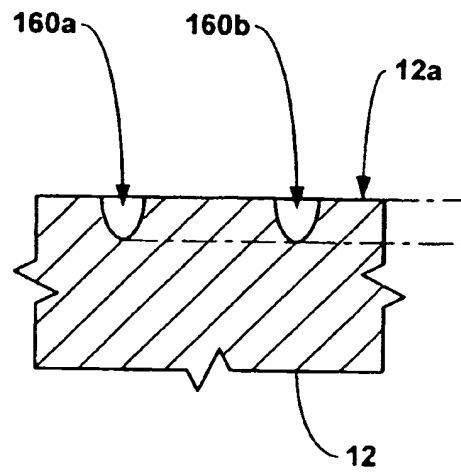


Fig. 17

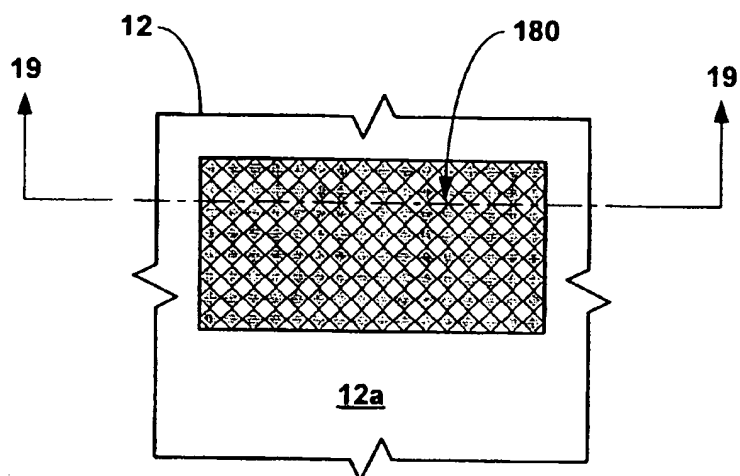


Fig. 18

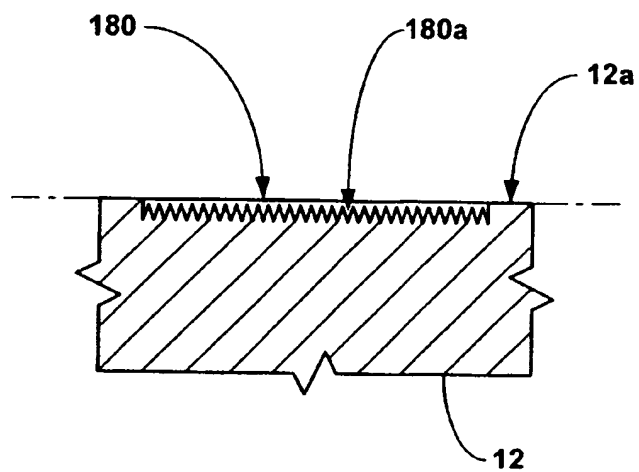


Fig. 19

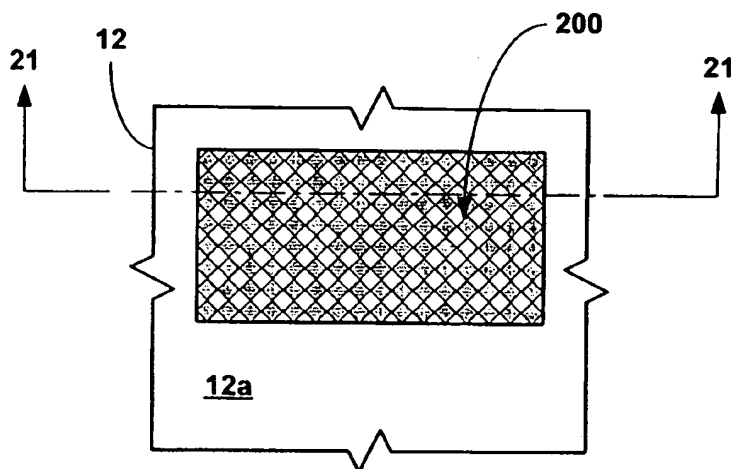


Fig. 20

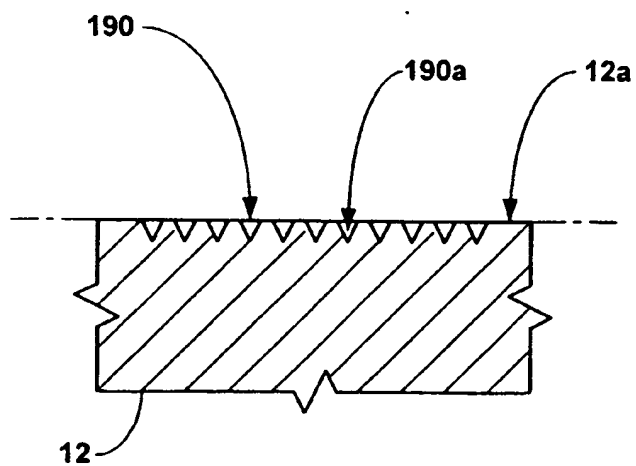


Fig. 21

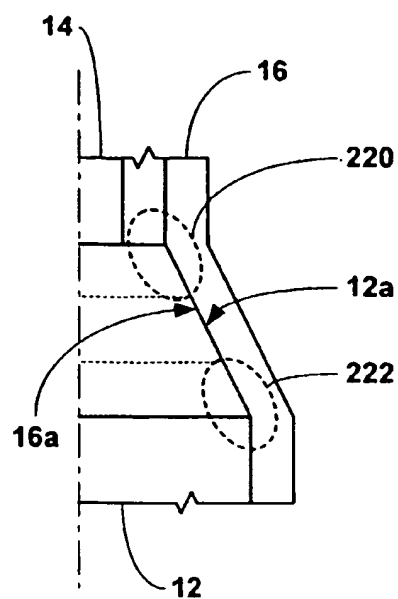


Fig. 22

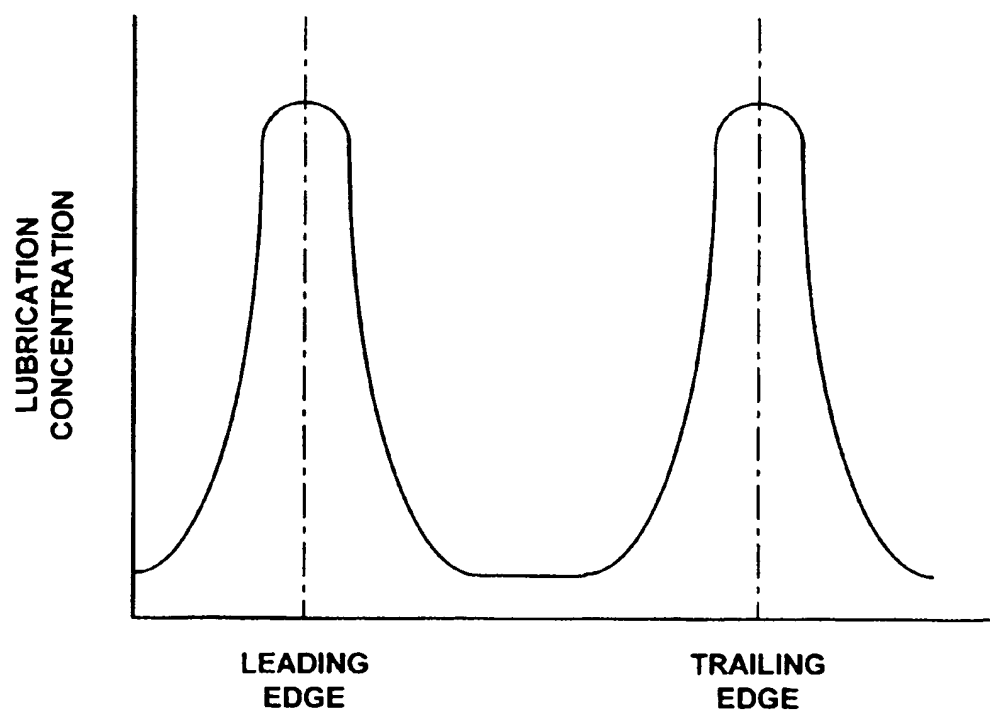


Fig. 23

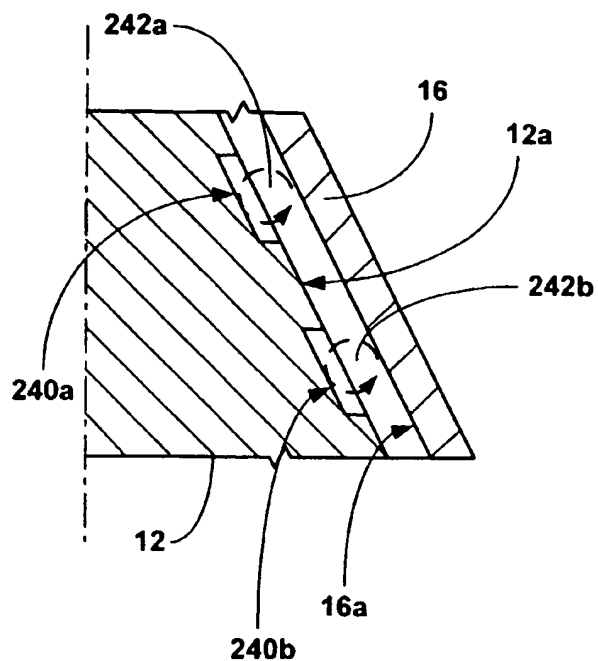


Fig. 24

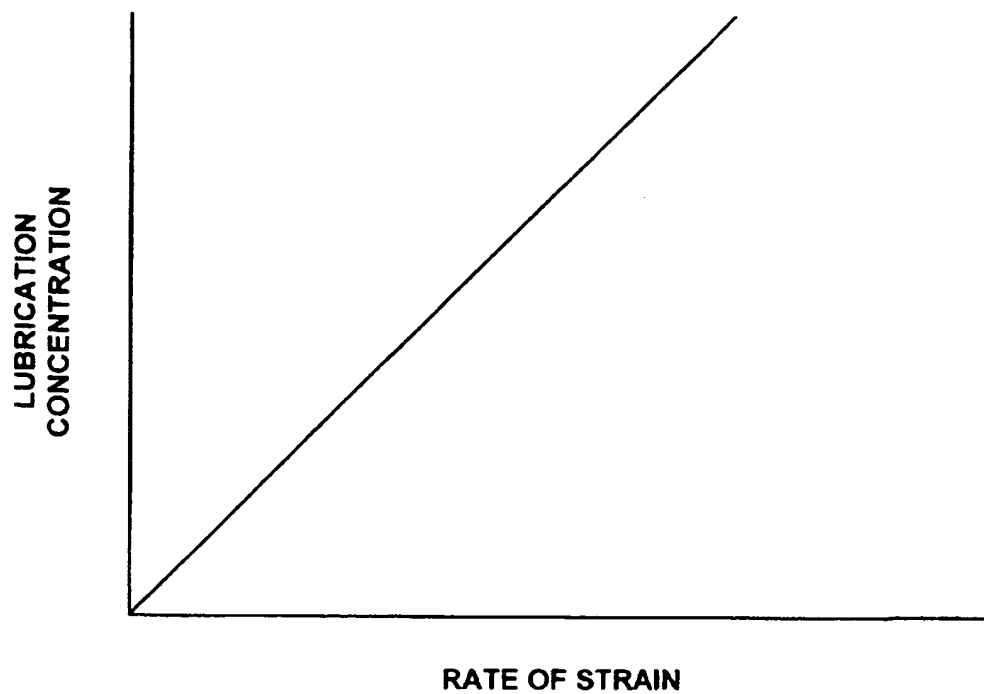


Fig. 25

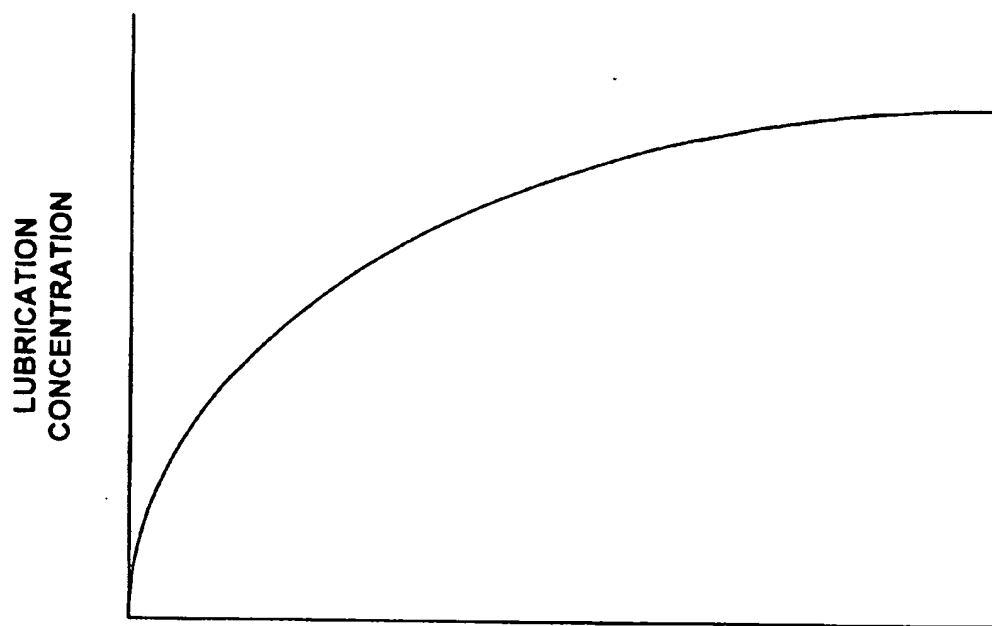


Fig. 26

RATE OF STRAIN

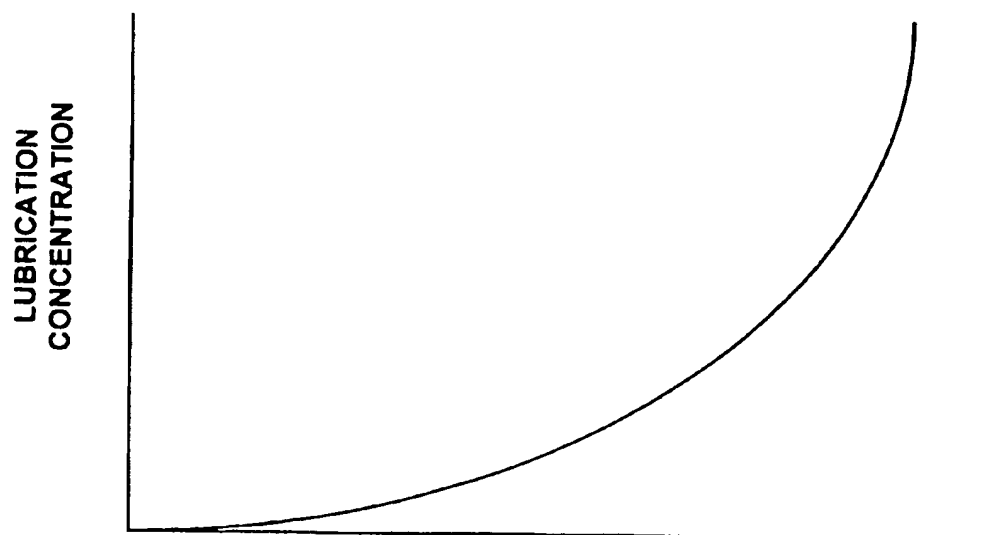


Fig. 27

RATE OF STRAIN

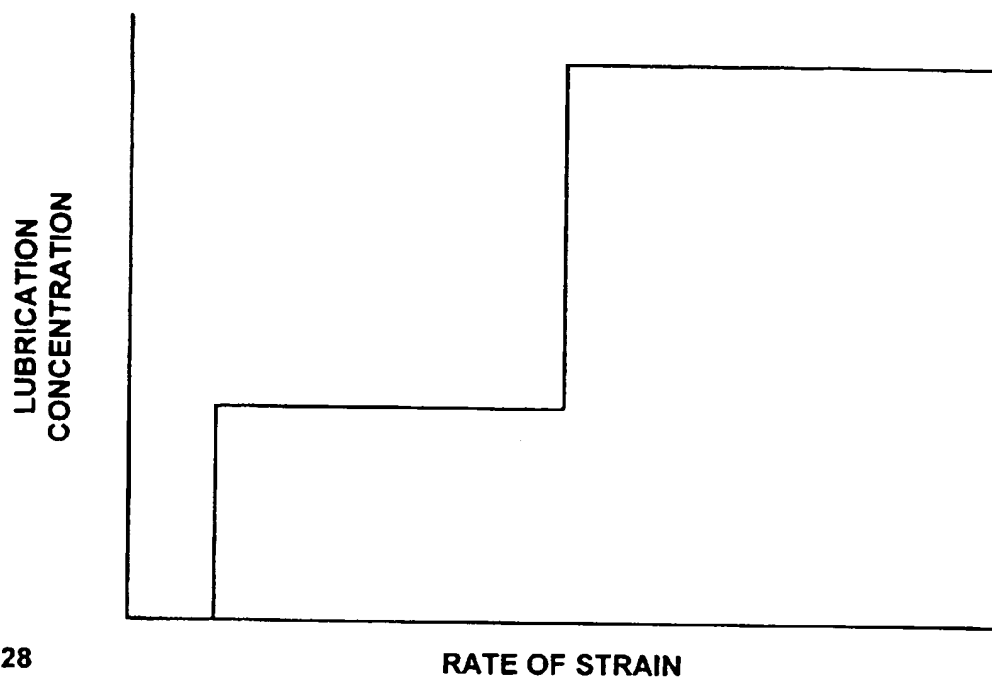


Fig. 28

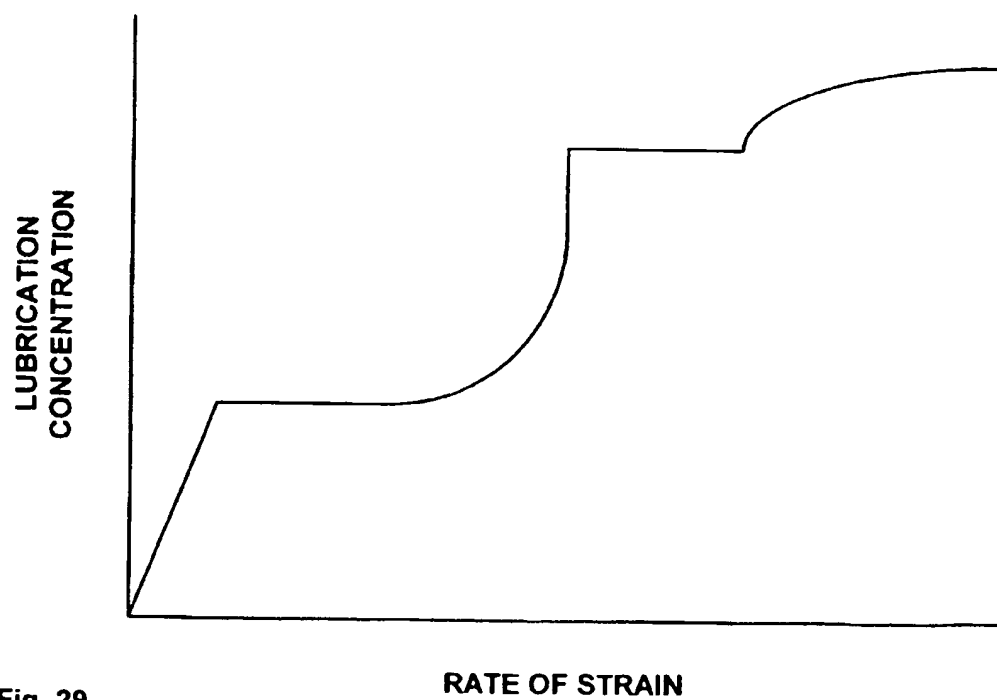


Fig. 29



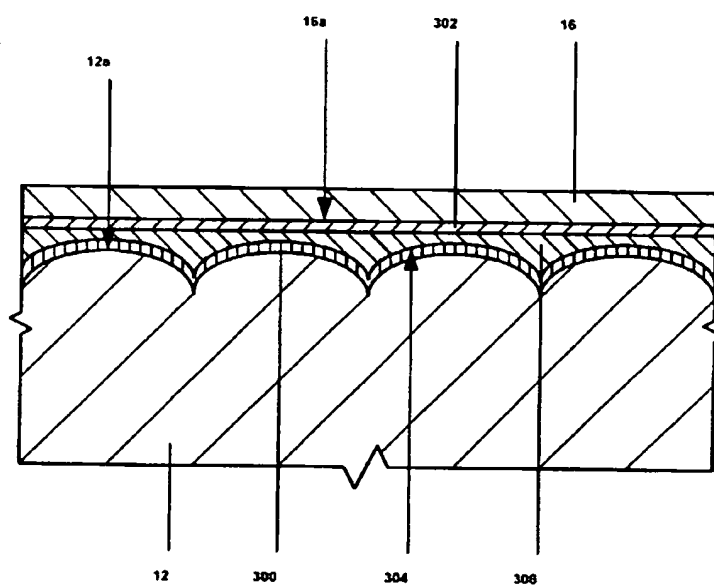


Fig. 30

**Typical 3-D Surface View of the D2 Steel  
Cone after Multiple Expansion of the 1-5/8" Pipe**

Fig. 31a

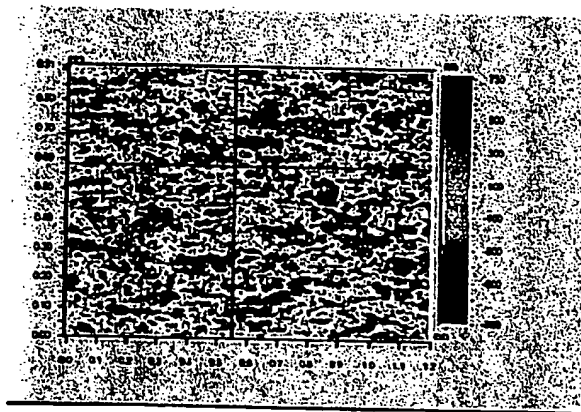


Fig. 31b

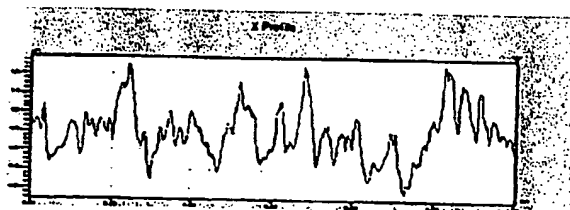
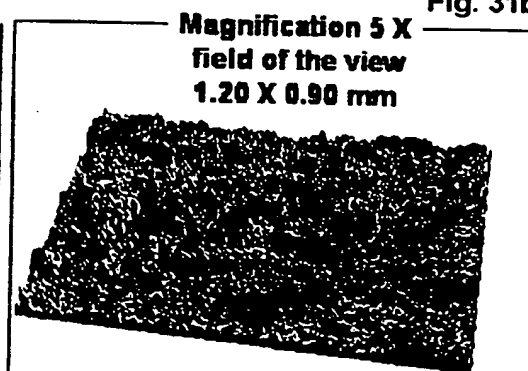


Fig. 31c

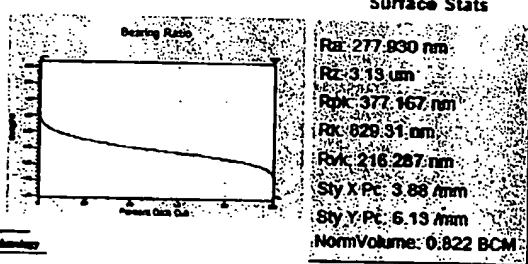
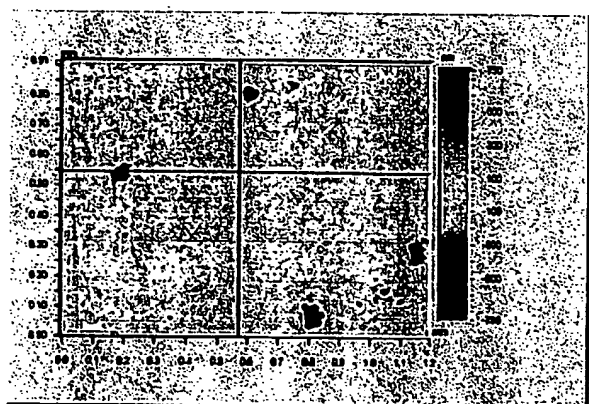


Fig. 31d

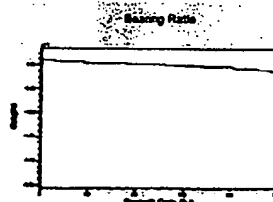
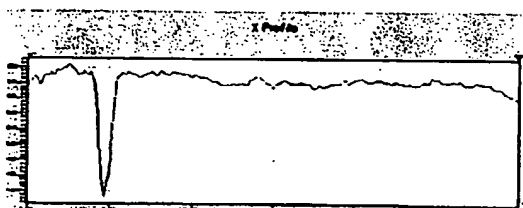
**Typical 3-D Surface View of the Used Advanced DC53  
Steel Cone with Phygen Film and REM Polishing**



Magnification 5 X  
field of the view  
1.20 X 0.90 mm



**Fig. 32b**



Surface Stats

Ra: 60.205 nm  
Rz: 1.99 um  
Rpk: 25.009 nm  
Rk: 152.12 nm  
Rvk: 92.963 nm  
Sty X Pc: 2.21 /mm  
Sty Y Pc: 3.53 /mm  
NormVolume: 0.047 BCM

Multiple Monitoring

**Fig. 32c**

**Fig. 32**

330

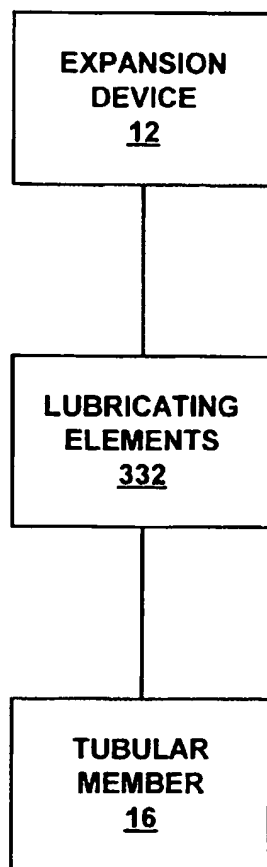


Fig. 33

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